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Effective Sampling Techniques for Particulate Emissions from Atypical Stationary Sources

FluiDyne Engineering Corp.
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Final Report

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16. ABSTRACT

Sampling techniques for measuring particulate emissions from four "atypical" stationary source categories were developed and evaluated. The categories include low effluent velocity streams, extended dimensions, partially or totally unconfined flow, and saturated gas streams or gas streams with entrained liquid droplets. Research included literature surveys, laboratory model testing, and field testing of instruments and techniques on three specific sources -- gravity roof ventilators, grain dryers, and wet scrubbers. These three sources served as representative examples of the four atypical source categories.

The sampling techniques recommended for roof ventilator emission measurements include a high volume particulate sampler and a heated thermopile anemometer deployed near the base of the ventilator. The same instruments, deployed at the lower exhaust, are recommended for grain dryer emission measurements. An EPA Method 5 type sampling train, an inertial droplet separator, and a Fecheimer probe are recommended for use in wet scrubber emission measurements.

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Final Report

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ABSTRACT

Techniques and instrumentation for use in measurement of particulate emissions from "atypical" stationary sources were developed and evaluated. The four atypical source categories studied are low velocity effluent streams, emission planes having one or more extended dimensions, partially or totally unconfined flow, and saturated gas streams or streams with entrained liquid droplets. Basic characteristics of these source categories were identified through literature and personal contact surveys. The research program also included laboratory model testing and field testing of several atypical stationary sources.

Three specific sources - gravity roof ventilators, grain dryers, and wet scrubbers - were selected to provide the basis for the development program for the four source categories. The sampling technique recommended for roof ventilator emission measurements includes a high volume particulate sampler and a heated thermopile anemometer deployed near the base of the ventilator. The same instruments, deployed at the louver exhaust, are recommended for grain dryer emission measurements. An EPA Method 5 type sampling train, an inertial droplet separator, and a Fecheimer probe are recommended for use in wet scrubber emission measurements. These techniques and instruments were evaluated as to the degree of reliability of emission measurements in the specific sources as well as applicability to general atypical stationary sources.

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SECTION 1

INTRODUCTION

The capability to determine particulate emission levels from stationary sources is of primary importance in programs intended to control air pollution for two reasons. First, reliable emission levels must be established in order to assess the severity of a pollution problem and, if necessary, set standards for its control. Second, in order to enforce compliance with established standards, emissions from a given source must be accurately determined. Procedures for selection of sampling sites, velocity measurements, and determination of particulate concentration have been established by the United States Environmental Protection Agency (Ref. 1) for emission sources characterized by well defined and constrained flow fields with velocities greater than 2 to 4 m/sec. Studies such as Ref. 2 have examined the reliability of emission measurements in stationary sources, such as exhaust stacks and ductwork in large power plants, which fall into this category.

As programs to control emissions have met with success, more interest has been focused on stationary emission sources in which the velocity, flow fields, and particulate concentrations are not well defined or the effluent gases are not confined by an accessible exhaust stack. Emission sources of this nature are generally classified as "atypical". The intent of this study is to examine the particulate emissions from stationary sources characterized by one or more of the following:

1. low velocity (less than 2 m/sec);
2. one or more extended dimensions;
3. partially or totally unconfined flow;
4. saturated gas streams or gas streams with entrained liquid droplets.

An overall evaluation of atypical emission sources will be presented first, followed by a discussion of the implementation of the above program for each of the selected sources. Sampling techniques and strategies will be discussed for flow and particulate concentration measurement related to several specific atypical emission sources. The methods will be discussed with regard to their usefulness for these specific applications as well as their applicability to other atypical sources.

The particular applications which will be discussed are roof ventilators (representing a low velocity/extended dimension source), grain dryers (partially unconfined flow) and wet scrubbers (entrained liquid droplets). Roof ventilators and grain dryers were chosen as primarily representative of these particular characteristics for determination of sampling techniques, although both roof ventilators and grain dryers may be classified as having characteristics under Items 1, 2 and 3.

Having identified these specific applications as representative of the various atypical source categories, the basic procedure followed in investigating each emission source was as follows:

1. Identification of typical characteristics of the source through preliminary field testing;
2. Design and fabrication of a representative laboratory model of the source;
3. Testing of sampling techniques in the controlled model environment, identification of a useful sampling technique, and evaluation of accuracy;
4. Final field tests, if necessary, to confirm the applicability of the sampling technique to actual field situations;
5. Assessment of the applicability of the selected sampling technique to other atypical sources.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations based on the program for evaluation of techniques and instrumentation for particulate emissions from atypical emission sources are presented in the following.

ROOF VENTILATOR EMISSIONS

The recommended sampling technique utilizes a heated thermopile anemometer and a high volume particulate matter sampler deployed at sampling locations near the base of the roof ventilator. Widthwise velocity surveys of on the order of 4 to 6 points at each sampling location were required to determine the average velocity at any given time. The number of sampling locations for a given length of roof ventilator must be determined for each application; an example based on field tests at a secondary aluminum foundry showed that three sampling locations were required for a 15.24 m ventilator. Engineering judgment should be used to determine a balance between economic considerations and the maximum amount of information obtainable in selecting the number of sampling locations when making emission measurements.

GRAIN DRYER EMISSIONS

The recommended sampling technique involves the use of the same instrumentation as used for roof ventilator emissions, in this case to be deployed at the surface of the exhaust louvers. A balanced matrix sampling strategy should be adopted. The total number of sampling points should be chosen to assure that the entire traverse can be completed during a period of relatively steady operation of the grain dryer.

WET SCRUBBER EMISSIONS

The recommended sampling technique includes velocity surveys with a Fecheimer type probe, humidity measurement with an inertial droplet separator type probe, and particulate concentration measurement with a Method 5 type sampling train. The number of sampling points should be determined from EPA Method 1.

GENERAL ATYPICAL EMISSION SOURCES

The basic characteristics of a general atypical emission source should be assessed. The techniques discussed above should then be selected according to the characteristics of the emission source which categorize the source in one of the areas considered in this study.

FURTHER STUDY

The limited scope of the present study did not allow complete answers to some of the questions in the extremely broad area of atypical emissions. Two areas toward which further study should be directed are:

1. Collection and evaluation of more data on the required number of sampling points for sources with extended dimensions, and
2. development of the reliability of inertial droplet separators.

SECTION 3

CLASSIFICATION AND EVALUATION OF EMISSION SOURCES

A survey of a number of atypical emission sources was made in order to determine which of the characteristics of interest apply to the various sources and, furthermore, to attempt to rank these sources in importance for consideration in this study. Information was extracted from the general literature as well as from contacts with instrumentation manufacturers, commercial firms engaged in emission measurements, eight state pollution agencies in eight different EPA regions, and EPA personnel.

Table 1 includes a list of several atypical emission sources and classifies them with respect to the various characteristics. The term "low velocity" here refers to sources having emission stream velocities which may often be less than 2 m/sec. Sources such as roof ventilators and louvered panels confine the flow for a short path length and are characterized here as "partially confined." The distinction is drawn between partially confined sources and unconfined sources, such as open field burning or agricultural tilling. Brief descriptions of some of the sources outlined in Table 1 and evaluations of the degree of importance of the various sources are included in the following.

EMISSION SOURCES WITH LOW VELOCITY AND/OR EXTENDED DIMENSIONS

Partially Confined Emission Sources

Several partially confined emission sources are listed in Table 2 together with information extracted from Refs. 3 through 8 concerning emission characteristics of these sources. Partially confined sources are often also characterized by one or more extended dimensions and low velocity effluent streams, as are the sources listed in Table 2. The particular configuration of each source type, however, will usually establish one or two of these characteristics as the primary factor or factors in defining a sampling technique.

TABLE 1. CLASSIFICATION OF SOURCES WITH RESPECT TO EMISSION MEASUREMENT PARAMETERS

Source	Low Velocity	Extended Dimensions	Confinement			Saturated Gas	Liquid Droplets	Weather Sensitive
			Duct	Partial	None			
Roof ventilators	x	x		x				x
Grain dryers	x	x		x				x
Wigwam incinerators	x			x				x
Unload grain box cars-trailer trucks into deep hoppers	x	x		x				x
Agricultural tilling	x	x			x			x
Unpaved road dust	x	x			x			x
Open field burning	x	x			x			x
Construction and land excavation	x	x			x			x
Open baghouses	x	x			x			x
Open incinerators	x	x			x			x
Mining and quarry activities	x	x			x			x
Aggregate stockpiles	x	x			x			x
Handling & transfer at:								
Grain elevators	x	x			x			x
Cotton gins	x	x			x			x
Cement plants	x	x			x			x
Asphalt plants	x	x			x			x

TABLE 1 (CONT'D)

Source	Low Velocity	Extended Dimensions	Confinement			Saturated Gas	Liquid Droplets	Weather Sensitive
			Duct	Partial	None			
Open vats	x	x			x	x		
Wet scrubber outlets			x			x	x	
Absorber exhaust sulfuric acid plants			x			x	x	
Saturators and blowers-asphalt roofing mfg.			x			x	x	
Paint booths			x			x	x	
Industrial dryers, e.g. plywood veneer dryer			x			x		
Ventilators emitting oil mist, e.g., machine shop, underground construction			x			x	x	

TABLE 2. PARTIALLY CONFINED EMISSION SOURCES

Source	Velocity at Plane of Emission m/sec	Avg. Particulate Loading gm/m^3	Particulate* Size	Emission Rate Factor gm part. per Kg of product	Estimated Total Annual Emissions metric tons
Roof Ventilators**	0.5 - 5				
1) Aluminum mill reduction cells					
a) H.S.Soderberg		0.07-4.6	Range down to submicron	72	32,000
b) V.S.Soderberg				42	9,100
c) Prebake				32	18,200
2) Open hearth steel furnaces					306,000
a) No oxygen lancing		0.9	50% < 5 µm	4	
b) With oxygen lancing		3.4	45% < 5 µm	11	
3) Electric arc steel furnaces					16,500
a) No oxygen lancing		0.2-5	60% < 5 µm	5	
b) With oxygen lancing		2.3-25	60% < 5 µm	5	
4) Iron Foundary furnaces		2.3-7	10% < 5 µm	8	100,000
Grain Elevators					
1) Grain Dryers	~3	9-80	Geo. means Oats 3.1 µm Wheat 2.1 µm	3-3.5	35,000
2) Grain loading/ unloading		0.25		1.5	110,000
Wig-Wam incinerators	~3	0.39	24% < 2 µm	5	120,000

* Size distribution information based on % by weight less than stated size.

** The figures tabulated represent total emission quantities through all controls and exhausts for the activities listed and are included in order to establish their relative importance.

Roof Ventilators

Roof ventilators as emission sources are found in a number of industrial applications, some of which are indicated in Table 2. Continuous gravity ventilators are typically utilized in situations requiring the removal of large heat loads. Basically, two styles of gravity ventilators are marketed commercially. Figures 1 and 2 illustrate the two basic types. The type with a single emission plane (Fig. 1) may extend along the entire length of a building and is generally referred to as a "continuous roof ridge ventilator", while the two-channel exhaust style (Fig. 2) is usually denoted by the terms "monitor" or "monitor attachment". The term "roof monitor" however, is often used as a description of either style of gravity ventilator or even certain types of powered ventilators.

Gravity ventilators find application in steel and aluminum mills, foundries, forge shops and glass plants, as well as warehouses, zoos, and other locations where air conditioning units are not economically practical due to large heat loads and/or large interior spaces. Both types of prefabricated ventilators, continuous roof ridge ventilators and roof monitors, are commercially available in 10 ft. lengths which may be spliced together to form runs of any desired length. The continuous roof ridge ventilator is available in sizes having throat widths ranging from 4 in. to 15 ft. and heights of less than 1 ft. to 18 ft. above the roof peak. The monitor type is available with openings ranging from 3 ft. to 15 ft. Both types are equipped with dampers which can be opened or closed to exhaust or retain building heat as required.

Roof ventilators often extend along the entire length of a roof ridge. Heat, fumes and particulate matter which evade primary control devices are propelled upward with thermal currents and may be emitted through the roof ventilator, which may often be considered a line source due to the large length dimension involved. Particulate emissions from roof ventilators typically consist of fine particles which closely follow the gas streamlines. This is due in part to the relatively small particulate emitted from typical industrial situations in which roof ventilators find application, as seen in Table 2, and in part to the fact that larger particulate tends to settle out before reaching the roof line or to be collected by primary control devices, when used. The volume of emissions is dependent upon wind speed, temperature, building design, louver adjustment, and level of activity in the ventilated area. Table 3 is a sample from a manufacturer's bulletin (Ref. 9) which illustrates the effects of temperature, height, and wind speed on flow capacity through a roof ventilator. Such tables are generally calculated on the assumption of wind direction perpendicular to the ventilator length, based on the negative pressure which develops as the flow passes over the ventilator

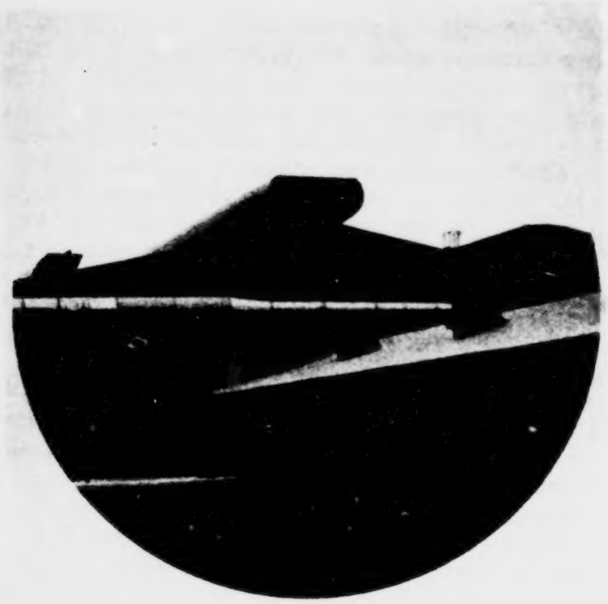


Figure 1. Continuous roof ridge ventilator

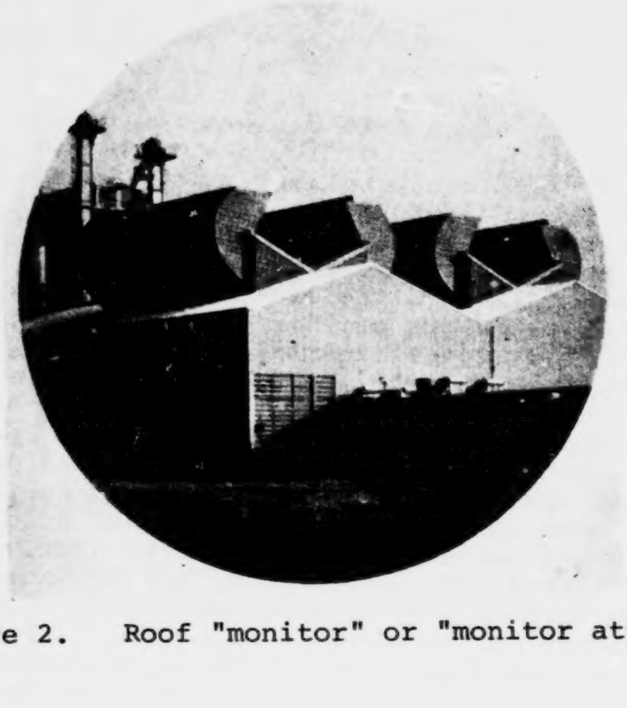


Figure 2. Roof "monitor" or "monitor attachment"

TABLE 3. PERFORMANCE TABLE FOR GRAVITY ROOF VENTILATORS (Ref. 9)

		C.F.M. Per Square Feet of Ventilator Throat Opening At Wind Velocities of:			
Temp. Diff.	Height Above Air Inlet	2 MPH	4 MPH	8 MPH	10 MPH
	10 ft.	193	281	395	457
	20	236	324	438	500
10°F	30	271	359	473	535
	40	298	386	500	562
	50	323	411	525	587
	10 ft.	236	324	438	500
	20	298	386	500	562
20°F	30	345	433	547	609
	40	385	473	587	642
	50	414	502	616	678
	10 ft.	271	359	473	535
	20	345	433	547	609
30°F	30	403	491	605	667
	40	451	539	653	715
	50	494	582	696	758

1 foot = .3048 meters

and creates an aspirating effect. Winds directed along the length of a ventilator will have much smaller effects than indicated in Table 3.

Certain general principles for roof ventilator design and performance calculations are specified in handbooks, such as Ref. 10. Detailed analyses of the flow are not available, however. In general, it may be said that flow rate and particulate concentration in roof ventilator exhausts are poorly understood, due to the large number of factors which affect performance.

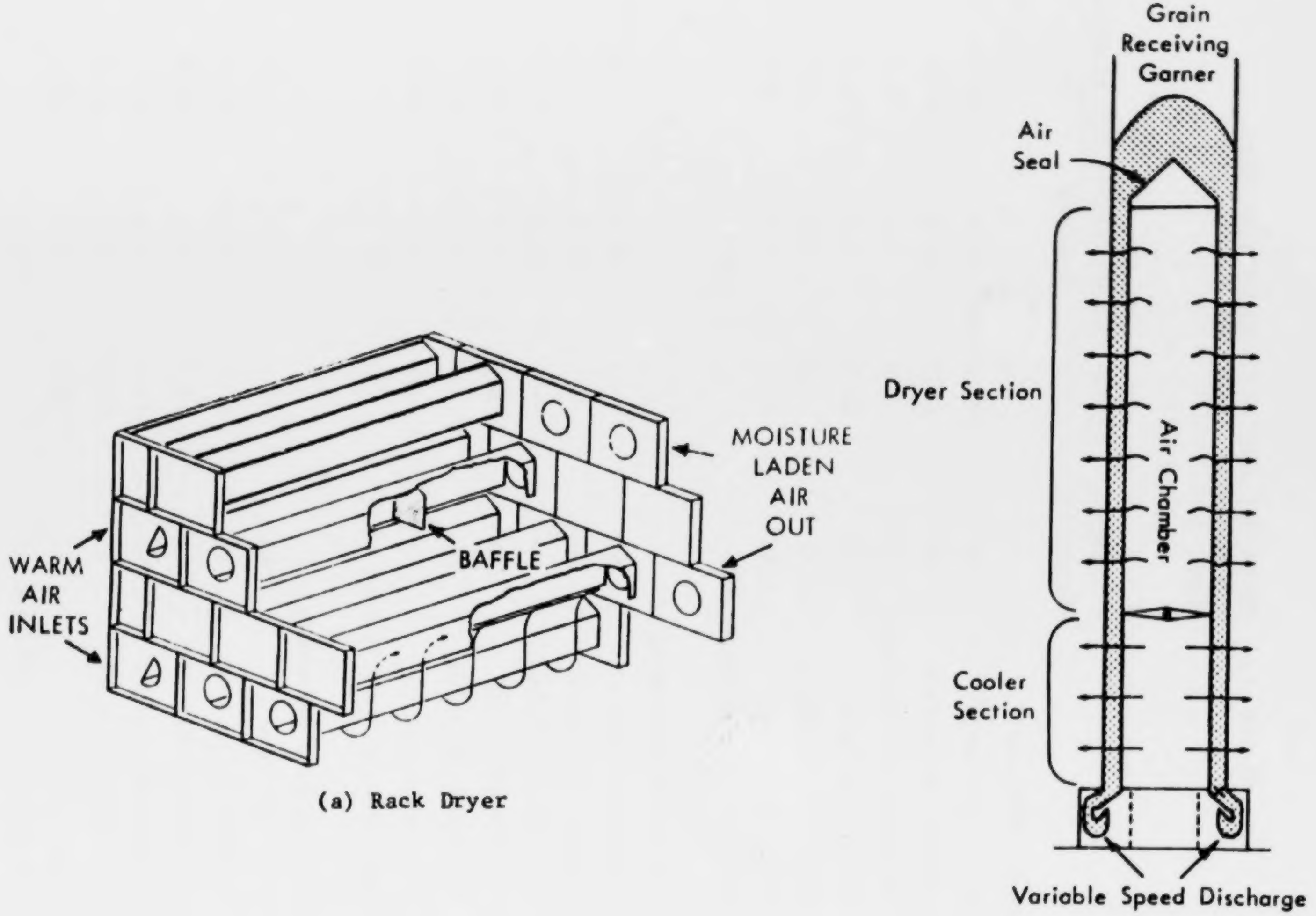
An indication of the importance of roof ventilators as emission sources is given by Tables 4 and 5. This information was extracted from Ref. 11, which is a study of only one of the industrial applications listed in Table 2, the primary aluminum industry. This data is based on a survey of aluminum production facilities throughout the United States. As indicated in Tables 4 and 5, since the primary collection efficiency of most aluminum process facilities is quite high and secondary collection is either very low in efficiency or nonexistent, the particulate emission through roof ventilators generally equals or exceeds the total emissions from primary particulate control systems. Table 6 includes data, extracted from Ref. 11, related to EPA tests of a single vertical stud Soderberg potline, which indicates similar conclusions.

Grain Drying and Handling

A number of partially confined emission sources are found in the grain and feed industry, one of which is grain drying. Grain drying is required when the moisture content of grain received at an elevator is too high for the grain to be safely stored. Drying is normally required when handling corn, although many other grains may require drying under certain conditions. Two common types of grain dryers, rack and column dryers, are illustrated in Fig. 3. Heated air or combustion products are generally used as the drying medium, and newer grain dryer designs often incorporate continuous recirculation of a portion of this heated air for higher drying efficiency.

A survey of grain elevators in 1973 indicated that roughly 1.6 million bushels of grain are dried annually (Ref. 6). Contacts with agricultural associations and pollution control agencies indicated that virtually all corn elevators use grain dryers, while dryers are not as prevalent in handling wheat and other types of grain. Overall, grain dryers are found to have a large degree of application.

Emission levels for grain dryers, extracted from Ref. 6, are indicated in Table 7. Several other emission sources in the grain and feed industry, such as headhouses, are indicated


WARM
AIR
INLETS
BAFFLE
MOISTURE
LADEN
AIR
OUT
Grain
Receiving
Garner
Air
Seal
Dryer Section
Air Chamber
Cooler
Section
Variable Speed Discharge

(a) Rack Dryer

(b) Column Dryer

Figure 3. Rack and column type grain dryers (from Ref. 6)

TABLE 4. INDUSTRY REPORTED EMISSION DATA FOR PRIMARY ALUMINUM FACILITIES (Ref. 11)

	% Capacity Reporting	kg Particulate/Metric Ton Aluminum		
		high	average	low
Prebake Potlines				
Total effluent	60	88.6	47.2	22.5
Primary collection	83	84.5	43.8	21.6
Secondary collection	65	7.8	4.0	2.0
Primary emission	76	12.5	4.6	1.1
Secondary emission	65	7.8	4.0	2.0
Total emission	65	16.3	8.1	3.5
Overall control efficiency			81%	
Vertical Stud Soderberg				
Total effluent	--	----	39.2	----
Primary collection	--	----	22.0	----
Secondary collection	--	----	11.0	----
Primary emission	89	6.5	4.4	2.2
Secondary emission	--	----	6.7	----
Total emission	--	----	11.7	----
Overall control efficiency			70%	
Horizontal Stud Soderberg				
Total effluent	93	52.0	49.2	41.8
Primary collection	93	42.0	39.1	31.4
Secondary collection	93	10.4	10.1	10.0
Primary emission	93	10.1	8.9	8.5
Secondary emission	93	10.4	10.1	10.0
Total emission	93	20.5	19.0	18.5
Overall control efficiency			61%	

TABLE 4 CONT'D

	% Capacity Reporting	Kg Particulate/Metric Ton Aluminum high	average	low
All types				
Total effluent	63	88.6	47.7	22.2
Primary collection	82	84.5	40.3	16.4
Secondary collection	71	7.8	6.9	2.0
Primary emission	82	24.4	5.9	1.1
Secondary emission	71	7.8	6.4	2.0
Total emission	71	23.5	12.3	3.5
Overall control efficiency			73%	

TABLE 5. SUMMARY OF EMISSION DATA - PRIMARY ALUMINUM INDUSTRY (Ref. 11)

	Emission Factor kg Particulate/Metric Ton Aluminum			
	Prebake	Vertical Stud	Horizontal Stud	All Types
Total effluent	47.2	39.2	49.2	47.7
Primary emission	4.6	4.4	8.9	5.9
Secondary emission	4.0	6.7	10.1	6.4
Secondary collection	4.0	11.2	10.1	6.9
Portion of total effluent emitted through roof monitor	8.5%	17.1%	20.5%	13.4%
Efficiency of secondary (roof monitor) control	50%	63%	50%	52%

TABLE 6. EMISSION FACTORS FOR A VERTICAL STUD SODERBERG POTLINE EPA TEST RESULTS (Ref. 11)

	Emission Factor kg Particulate/Metric Ton Aluminum	
	(1)	(2)
Primary collection	45.63	33.80
Secondary collection	13.56	13.34
Primary emission	0.06	0.06
Secondary emission	4.77	2.92
Total emission	4.83	2.97
Primary efficiency	99.86%	99.84%
Secondary efficiency	64.85%	78.15%
Overall efficiency	91.85%	93.70%

(1) Average of 3 tests.

(2) Average of 2 tests; 1 test deleted due to stud blow during test.

TABLE 7. SUMMARY OF GRAIN DRYER EMISSIONS AT ELEVATORS (Extracted from Ref. 6)

	Total Emissions (1971) (metric tons/yr)
Country Elevators	2.14×10^4
Terminal Elevators	2.53×10^3
Export Elevators	3.82×10^2

in Ref. 8 as having higher total annual emissions than grain dryers. However, grain dryers present unique problems in emission measurement due to the large surface area of the emission plane, low velocities, and large particulate size (Ref. 6). While reliable emission measurements have been obtained for most emission sources in the grain and feed industry using Method 5 equipment and techniques, emission data for grain dryers has been shown to be very unreliable due to these sampling problems.

In additon to hulls, cracked grain, weed seeds, and field dust, grain dryer emissions include other large, lightweight particles denoted as "chaff", or "beeswing" in the case of corn, which break off from the grain during drying and handling. The low specific gravity of emitted particulate matter intensifies the sampling and collection problems associated with the partially unconfined nature of grain dryers as an emission source. The emission level is affected by a number of factors, including the type of dryer, the type and hardness of the grain, the moisture content of the grain (typically 10-20%) and the amount of foreign material in the grain.

Another partially confined source related to grain elevators is the deep receiving hopper. Grain is dropped from boxcars or trucks in surges from a height of 1 to 5 m (Fig. 4). The falling grain particles disperse as they accelerate and induce into motion a column of air moving in the same direction. When the mass of particles strikes the hopper bottom, the dissipated energy results in extreme turbulence as well as abrasion and dispersion of the particles. The dust generated may form a plume of 100% opacity and sufficient volume to envelop an entire boxcar. Sampling of such sources is usually accomplished by assessment of the ambient conditions.

Incinerators

Incineration of sawmill wood and bark wastes is a primary air pollution source in the lumber industry. Effluent gas velocities from wigwam incinerators may be on the order of 3 m/sec. Air quality problems may often be reduced by improvements in combustion efficiency.

Unconfined Emission Sources

Emission sources from which the pollutants are not constrained by process streams are classified as unconfined sources. Unconfined, or fugitive, emissions are generated by natural means as well as industrial processes. Dust arising from wind erosion has been estimated to comprise 20% of the total annual worldwide aerosol production (Ref. 13). Fugitive dust sources are now being recognized as possible causes for regional noncompliance with air quality standards.

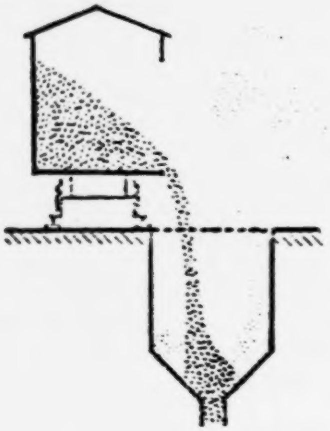


Figure 4. Unloading grain from box-car into a deep hopper (Ref. 12)

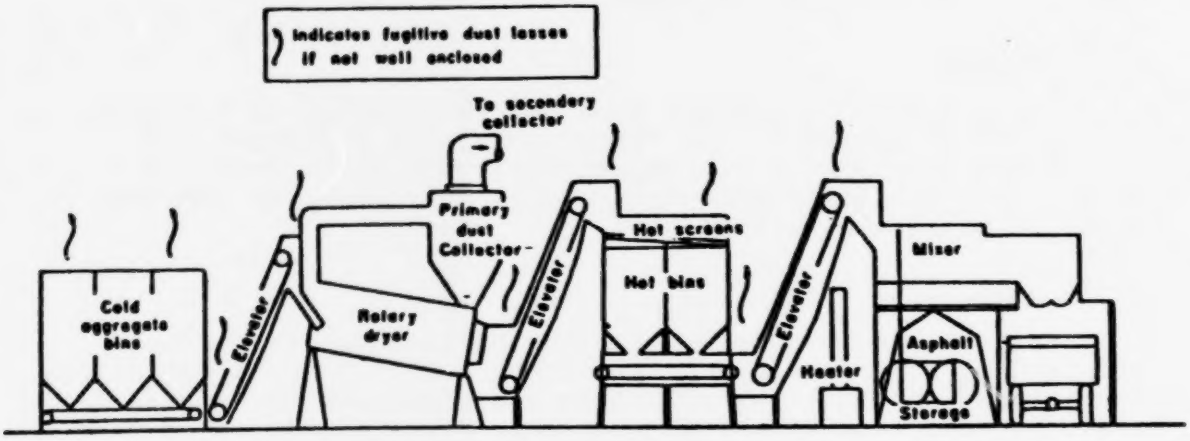

indicates fugitive dust losses if not well enclosed
To secondary collector
Primary dust Collector
Hot screens
Mixer
Cold aggregate bins
Elevator
Rotary dryer
Elevator
Hot bins
Elevator
Heater
Asphalt
Storage

Figure 5. Unconfined emission sources at a continuous mix asphalt plant (Ref. 5)

Several activities which may generate unconfined emissions are summarized in Table 8. The data presented in this table was extracted from Refs. 3 and 5. For many unconfined emission sources, published data is either of a qualitative nature or is unavailable.

Stone Crushing And Asphalt Plants

Fugitive emissions in the stone crushing industry can be generated by activities such as drilling, blasting, crushing, conveying, removal of fines, storage and loading. Most emissions are of heavy particles that settle near the source. Crushing is done in three stages, and the third crushing and screening processes contribute the major portion of the emission. The degree of enclosure of the processing and transfer areas and the degree to which control equipment is used in the various processes determine the quantity and concentration of emissions. Possible fugitive emission sources at asphalt plants are indicated in Fig. 5. Dust is generated at elevator transfer points, hot screens, and hot and cold aggregate bins.

Agricultural Burning

Smoke from agricultural field burning is composed primarily of carbon particles, ash, and various gases. These emissions cause odors and reduction of visibility. Emission plumes consist mostly of particles less than 1.3 microns in diameter, identified as medium-and large-molecule hydrocarbons which provide a serious potential for lung irritation (Ref. 14). Emissions from field burning are highly dependent on wind, ambient temperature and type of fuel being consumed. Slash burning, primarily practiced in the Western United States to reduce the flammability of heavy slash concentrations after timber cutting, has been estimated by the United States Department of Agriculture to produce 5.5 million metric tons of particulate matter each year.

Emission Measurements and Standards

A number of studies have been made concerning the prediction of plume heights and concentrations related to unconfined sources using various dispersion models. Actual measurement of emissions from unconfined sources is poorly defined, however. Most measurement studies have utilized ambient monitoring equipment located in the vicinity of an emission source, often upstream and downstream of the source in the direction of the prevailing wind.

Ref. 15 includes empirical equations for emission factors of four categories of unconfined sources (agricultural tilling, unpaved roads and airstrips, heavy construction activities and aggregate storage piles) which are based on an extensive field testing program. The testing reported in Ref. 15 included

TABLE 8. UNCONFINED EMISSION SOURCES

Source	Average Particulate Concentration gm/m^3	Particle Size	Emission Rate Factor gm Particulate per kg Product	Estimated Total Annual Emissions metric tons
Crushing				
a) Stone	-	10-50μm*	8	4,150,000
b) Sand & Gravel	13-87	3.5-9.4μm*	0.05	42,000
Asphalt Plants	-	40% 10μm***	4	37,000
Agricultural Field Burning	.01-.06	0.5μm*	8.5	2,200,000
Cement Plants	2-35	30% 5μm***	26	172,000
Cotton Gins	.004-1.25	-	5kg/bale	41,000
Aggregate Stockpiles	-	-	0.0-0.5%**	6,000,000

* Typical mass median diameter

** Stockpile losses due to wind erosion

*** Size distribution information based on % by weight less than stated size isokinetic sampling of dust with specially designed equipment, conventional high volume sampler measurements and particle size measurements with high volume cascade impactors. Emission factors were related to meteorological and source parameters including properties of the emitting surface and characteristics of the vehicle or implement which caused the emission, and correction factors were developed to reflect regional differences in climate and surface properties.

Emission standards for unconfined sources are generally of a qualitative nature. Regulatory agencies have normally adopted regulations prohibiting airborne particulate matter from crossing property lines. Enforcement of such regulations is generally handled on a complaint basis.

EMISSION SOURCES WITH SATURATED GAS STREAMS OR ENTRAINED LIQUID DROPLETS

Effluent streams from certain industrial processes are characterized by saturation with various types of vapors or by the presence of entrained liquid droplets. Several emission sources of this type are listed in Table 9 along with emission data extracted from Refs. 3, 5, 8, 16, 17 and contacts with various information sources.

Cooling of exhaust gases from evaporators, boilers and stills below the dew point of any gaseous components, such as water or acid, can generate large quantities of liquid droplets. Wet scrubber control systems also introduce droplets into exhaust gases. Droplets formed by tearing of liquid sheets and ligaments and by splashing of liquid drops are generally 200 μm and larger. The mist formed by condensation of saturated vapor contains submicron droplets. Entrained liquid droplets may cause excessive corrosion, decrease in equipment performance, or loss of processed material in addition to the air pollution problems.

Sulfuric Acid Plants

The exhaust gases from sulfuric acid manufacturing plants are common sources of acid mist. Sulfuric acid is manufactured by either the chamber process or the contact process (Ref. 16). The primary emission source in the chamber process is the Gay Lussac Tower, whose function is to recover nitrogen oxides released in the manufacturing process. Aerosol concentrations may range from 0.2 - 1.2 gm/m^3. Over 90% of the particles, by mass, are larger than 3 μm in diameter.

The major emission source in sulfuric acid contact plants is the stack from the absorption tower, which removes most of the sulfur trioxide. Small amounts of unabsorbed sulfur trioxide and a larger quantity of acid mist are emitted to the

TABLE 9. EMISSION SOURCES WITH SATURATED GAS STREAMS OR ENTRAINED LIQUID DROPLETS

Source	Flow Rate Nm^3/min	Avg. Mass Concentrations gm/m^3	Particle Size	Emission Rate Factor gm part per kg of Product	Estimated Total Annual Emissions Metric Tons
Sulfuric acid plants					
Chamber process	55-370	0.2-1.2	10% < 3μm**	2.5	1,800
Contact process	140-1750	0.04-1.75	64% < 3μm**	1	3,600
Spent acid concentrators	1700	2-4	-	15	7,200
Asphalt Roofing Mfg.					
Blowers & Saturators	280-560	1.0-1.8	∿ 1μm	2	15,500
Plywood Veneer Dryers	-	-	-	$3\ Kg/1000\ m^2$	3,600
Wet Scrubber					
Downstream of Thermal Coal Dryer	600-5500	.070*	-	-	94,000*
Sewage Sludge Incinerators	850	0.3*			

* Estimate includes solid particulate.

** Size distribution information based on % by weight less than stated size.

atmosphere. The presence of a substantial number of particles smaller than 3 μm is evidenced by the appearance of a dense, white plume at the stack exit which does not necessarily reflect the mass concentration of sulfuric acid mist.

Several types of mist eliminators are used with varying degrees of success in removing the entrained droplets. Electrostatic precipitators and glass-fiber mist eliminators can achieve 92-99.9% collection efficiency over the entire particle size range. Stainless steel wire-mesh mist eliminators have low initial cost but have low efficiency under certain plant operations when the proportion of small particles is sharply increased. This occurs, for example, during production of oleum, a solution of free, uncombined sulfur trioxide. Tall stacks, on the order of 50 m or larger, have been shown to be effective in reducing acid spray emissions, since large particles tend to collect on the stack wall. Indications are that approximately 90% by mass of the total acid mist and spray from an absorber outlet has been collected in an 80 m stack.

Asphalt Plants

Another source of vapors and mists are the effluents from "blowing", or oxidizing of stills and saturators used in the manufacture of asphalt roofing. Blowing is accomplished by bubbling air through the liquid asphalt at a temperature of about 230-260°C for 8 to 16 hours. After blowing, asphalt is transferred to a saturation tank or spray area where it is sprayed onto one side of felt that is continuously fed from rollers. This is done in order to remove moisture from the felt which could cause blisters when the felt is saturated by passing it through a tank of molten asphalt.

The high application temperature causes vaporization of those asphalt components having lower boiling points. Moisture in the felt is also vaporized, which contributes to the formation of a mist of high opacity. Additional mists and vapors are emitted as the saturated felt is cooled. Particulate emitted from saturators is formed by condensation and, therefore, is likely to have a size on the order of 1 μm. Various hood and exhaust configurations have been devised for exhausting blower and saturator emissions which require volumetric capacities of 280-560 Nm^3/min.

Industrial Dryers

Industrial dryers are another source of vapor and liquid particulate emissions. Plywood veneer dryers are used to reduce the moisture content of green veneer panels from about 50% to less than 10% in long, heated, enclosed chambers. Dryer design varies greatly. Emission plumes are saturated with water vapor and other condensibles including wood resins, resin acids and wood sugars which form a blue haze when cooled. Volatile components include terpenes as well as unburned methane when gas-fired dryers are used. Emission factors are generally expressed in terms of pollutant weight per unit of surface area of 1 cm (or 3/8 in) plywood produced. Condensible compounds are estimated by Ref. 8 to contribute 63% of the emitted pollutant, while volatile compounds make up 37%.

Wet Scrubbers

Wet scrubbers have found application in a wide range of effluent control problems. There are many varieties of wet collectors, but they may generally be classifed as low energy or high energy scrubbers. Simple spray towers, packed towers, impingement tray scrubbers, and other configurations which operate with low pressure drop may be classified as low energy scrubbers. Efficiences can exceed 90-95%. Air pollution control systems for incinerators, fertilizer manufacturing plants, lime kilns, iron foundries, stone crushing operations, and clay product production commonly incorporate low energy scrubbers.

High energy, or Venturi, scrubbers incorporate a converging-diverging duct section to attain high gas stream velocity while scrubbing liquid is injected. Higher collection efficiency is realized, but the higher efficiency is accompanied by higher pressure drops requiring high power draft fans. Common applications for Venturi scrubbers include steel furnaces, pulp mills and foundry cupolas.

The three situations indicated in Table 9 are not representative of the large number of scrubber applications, but they do indicate the broad range of conditions which may be encountered in scrubber exhaust gases.

SELECTION OF SOURCES FOR TEST PROGRAM

After evaluating a number of emission sources, including the information presented in the previous sections as well as information found in Refs. 17-28, three specific sources were chosen for the test program. By limiting the actual test program to these specific emission sources, a reasonable amount of useful information about each of the selected sources was obtained within the alloted limits of the program. The selected sources are sufficiently representative of the atypical source categories of interest; therefore, the test program provided insight into sampling techniques for general emission sources possessing the various atypical source characteristics. The selected sources are discussed briefly in the following.

Roof Ventilators

Roof ventilators were selected as a representative example of two of the atypical source categories, emission sources characterized by (1) low velocity and (2) extended dimensions. The bases for this selection are the wide degree of application of roof ventilators, the significant emission levels associated with them and the clearly defined nature of the characteristics of the source (i.e., low velocity and extended dimension are clearly the outstanding features of roof ventilators).

Grain Dryers

Grain dryers were selected to represent the category of partially or totally unconfined flow. The choice of a partially confined source, rather than a totally unconfined source, was made in view of the overall philosophy of the program in regard to model studies. Modeling a partially confined emission source, such as a grain dryer, constitutes a reasonable extension of the sampling problem into the realm of this atypical source category without attempting to complicate matters to a degree which would very likely preclude any concrete results within the scope of the present study. The choice of grain dryers as the specific source was based on their common usage as well as the previously noted sampling difficulties cited by other investigators of grain dryer emissions.

Wet Scrubbers

The exhaust flow from wet scrubbers was chosen as the representative example of emission sources with saturated gas streams or gas streams with entrained liquid droplets. This choice was based on the popularity of scrubbers in pollution control systems and the resulting large number of applications in various industrial situations. In addition, the exhaust of a scrubber is generally a duct or stack, which lends itself well to modeling and laboratory testing.

SECTION 4

ROOF VENTILATOR SAMPLING TECHNIQUES

Continuous gravity roof ventilators, in typical applications, are primarily characterized by low velocity and extended dimensions. These two characteristics make emission measurement following EPA Method 5 sampling techniques inadequate. Under the present study, sampling methodology which has been applied to roof ventilators was reviewed, and techniques and instrumentation for measurement of roof ventilator emissions were evaluated following a test program as outlined in the Introduction.

REVIEW OF SAMPLING METHODOLOGY

Contacts with a number of commercial firms which have performed emission measurements in roof ventilator applications revealed that specific procedures for such situations have not been established. In general, sampling techniques and instrumentation have been selected for a given application on the basis of engineering judgment. Sampling techniques have often employed temporary collection hoods of some type, and generally the use of high volume samplers has been prescribed for particulate collection. The most frequently used velocity instruments were vane or propeller anemometers, followed in preference by hot wire anemometers. Reliability of emission measurements has generally been considered poor due to the low velocity, fluctuating, often circulatory flow characteristic of roof ventilators as well as the intermittent nature and low concentration of the particulate emissions from most roof ventilators.

A study of roof ventilator emissions at electric furnace operations led to the development of test methodology by Kreichelt and Keller (Ref. 29). Particulate concentration measurements were accomplished using standard high volume samplers suspended inside the roof ventilators, and velocity measurements were obtained using both hot wire anemometers and rotating vane anemometers. In this study, emission measurements were determined for a 60 m long roof ventilator both during periods of charging and tapping of the steel furnaces and during periods of so called "background" emission. Several high volume samplers spaced at 8.5 m intervals along the ventilator length were operated simultaneously; during charging and tapping operations, the samples were fixed at the midpoint of the monitor width due to the short duration of these operations, while the samplers were traversed across the width during background measurements. Velocity traverses were made independently of particulate concentrations measurements during charging and tapping operations, the total number of traverse points being dictated by the time duration of the operations. Velocity measurements during background periods consisted of 6-point traverses at each of 7 locations along the length of the roof ventilator.

Figure 6 indicates the sampling technique discussed in Ref. 29. No attempt was made to sample isokinetically due to the large velocity fluctuations observed. Variations as large as a factor of 6 were observed from point to point, yet overall average velocities from various surveys during the background periods agreed well. (The average sampling velocity did agree fairly well with the average effluent velocity.) An overall assessment of the test methodology in Ref. 29 concluded that it provided a technically feasible, but costly, method for determination of emissions from roof ventilators; the total time and cost estimate given in Ref. 29 was 4 months or more and $10,000-$20,000 to complete a single emission study.

Souka, et al (Ref. 30), described a sampling technique used to evaluate emissions from a 1.22 m x 91.5 m roof ventilator at a graphitizing facility. Three sampling systems (Fig. 7), each including a high volume sampler and an electric anemometer, were located at the midpoints of equal sections of the ventilator outlet. Baffle plates, roughly 3 m in length, were located about 3 m on each side of each sampling station to minimize wind crossflow effects.

The testing period reported in Ref. 30 was 160 hours of almost continuous sampling. Particulate collection filters were changed at times dictated by observing the decreasing flow rate through the samples. Velocity readings were obtained every 1.2 minutes and averaged over the appropriate sampling periods. Since isokinetic sampling could not be achieved due to the fluctuating effluent velocity, sampling rates were kept well below isokinetic rates in order to achieve conservatively high emission rate measurements. Emission rate determined by this method is indicated in Fig. 8 for one of the three sampling stations. The conclusion drawn from Ref. 30 is that the wide emission rate fluctuation observed dictates long sampling periods to obtain a true picture of actual emissions. Total cost for such an emission test were estimated to be on the order of $15,000-$25,000 (Ref. 31).

Federal regulations in regard to roof ventilator sampling were formulated in conjunction with emission standards for the primary aluminum industry in the form of EPA Method 14 (Ref. 32). This method substantialy follows the sampling

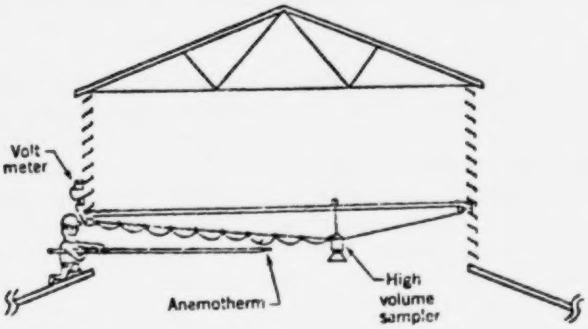

Volt meter
Anemotherm
High volume sampler

Figure 6. Cross section of roof ventilator showing test equipment (Ref 29)

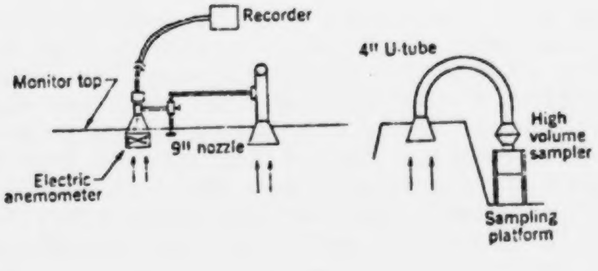
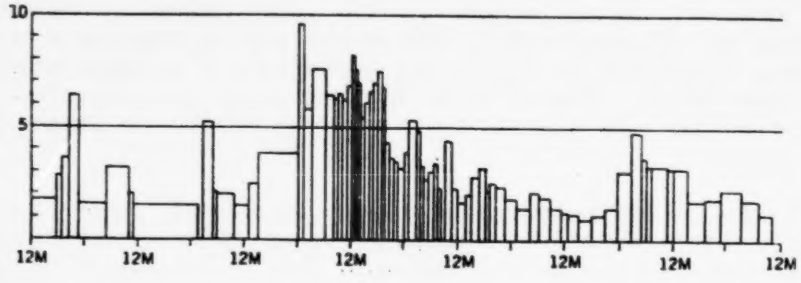

Recorder
4" U-tube
Monitor top
9" nozzle
Electric anemometer
High volume sampler
Sampling platform

Figure 7. Sample system (Ref. 30)



Time

Figure 8. Emission rate measurements, central sampling station (Ref. 30)

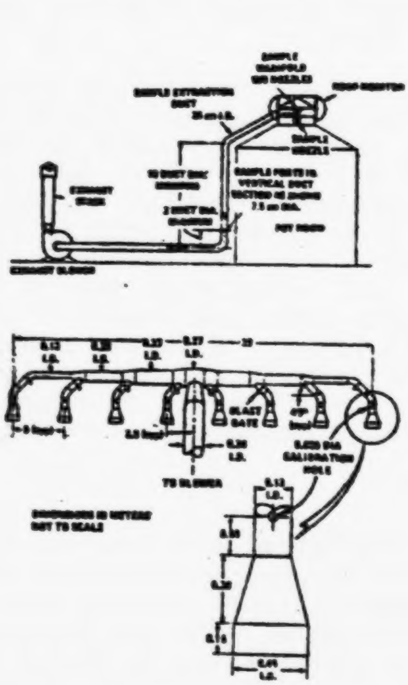

0.27
I.D.
BLAST GATE
TO BLOWER
I.D.

Figure 9. EPA Method 14 sampling system

method developed by Alcoa for roof ventilator sampling (Ref. 33). Particulate concentration measurements, following Method 14, are to be accomplished by means of a sampling network as outlined in Fig. 9. In this system, effluent gas is drawn through 8 nozzles, mounted near the center of the roof ventilator, to a manifold. The velocity through each nozzle, as measured with an S-tube inserted through the calibration holes shown in Fig. 9, is adjusted to the same value by means of blast gates or valves before emission measurements are made. Particulate sampling is then performed in the duct exhausting from the manifold. The length of the sampling manifold is to be 85 m or 8% of the total ventilator length, whichever is greater.

Velocity is to be determined by means of propeller or vane anemometers with electric output, appropriately protected from a dusty and corrosive environment. One anemometer is required for each 85 m of ventilator length, located at the center of equal length segments and permanently mounted at a point of average velocity as determined by a widthwise velocity traverse. Velocity readings are to be recorded at maximum time intervals of 15 minutes during a test; the sample rate during a test is to be adjusted such that the velocity inlet to the sampling nozzles equals the average velocity determined for the 24 hours preceding the test.

All of these methods described in the literature emphasize particulate concentration measurement through the collection of relatively large sample volumes (compared to EPA Method 5), employing standard high volume samplers, modified high volume samplers, or specially constructed high volume nozzles and manifolds. Volumetric flow rates determined from single point measurements or widthwise velocity traverses at a small number of locations along the roof ventilator length together with the concentration measurements have been used in these methods to determine total emission rates. With the exception of the baffle plates in Ref. 30, artificial collection apparatus is not recommended in the literature, in contrast to the general impression received through commercial testing firm contacts.

PRELIMINARY FIELD TESTS

The site selected for field testing was Hitchcock Industries in Bloomington, Minnesota, a secondary aluminum foundry. This facility has a number of roof ventilators, both of the powered and natural draft type. The particular roof ventilators chosen for initial field testing are pictured in Fig. 10. Each of these ventilators is a 15.2 m (50 ft) length of a configuration known as the Swartwout (42 inch) Heat Valve. The ventilator height is approximately 2 m; the base width is roughly 2 m and the exhaust plane at the top is about 1.5 m wide. The ventilators shown in Fig. 10 are located above a room containing six

Figure 10. Roof ventilators at Hitchcock Industries, Bloomington, Minnesota, viewed from the northwest

Figure 11. Typical roof ventilator exhaust at Hitchcock Industries site

gas-fired furnaces which are used to melt the aluminum stock. The roof ventilator exhaust configuration, which has two exhaust planes, is shown in Fig. 11.

Due to the low concentrations expected to be encountered, a high volume particulate sampler was chosen for the basic concentration measurement equipment. A Staplex Model TF1A high volume sampler was fitted with an extension probe and a 20.3 cm x 25.4 cm (8 inch x 10 inch) filter holder designed and fabricated by FluiDyne. The sampling probe is used with standard Gelman Type A glass fiber filters. The entire assembly is illustrated in Fig. 12. This sampling probe has a flow rate capacity as high as 2 m^3/min (70 ft^3/min).

Two velocity instruments were selected for the preliminary field tests, a Flowrite Model MRF vane anemometer and a Thermo-Systems, Inc. Model 1610 hot film anemometer. The hot film anemometer was a special high-temperature (160°C) version of the standard hot wire anemometer Model 1610. The hot wire anemometer was fitted with a protective collar designed and built by FluiDyne (Fig. 13) for a previous project in which velocities in the range of 0.03 -4.57 m/sec (0.1 - 15 ft/sec) had been successfully measured. The vane anemometer was a direct reading instrument with a range of 0.3 - 15.2 m/sec (50 - 3000 ft/min). Both instruments were mounted on extensions to be hand held for the velocity measurements. The hot wire anemometer was also fitted with an iron-constantan thermocouple for temperature measurement.

During two days of testing at the Hitchcock Industries site, particulate concentration and velocity measurements were accomplished at several locations in one of the roof ventilators shown in Fig. 10. The sampling planes and locations are indicated in Fig. 14. Particulate concentration measurements were made at stations 2, 3 and 4, in both the east and west sample planes, and velocity surveys included measurements at all 5 sampling stations in both sample planes.

During the field tests, the operations within the foundry were also observed. The furnaces were loaded with aluminum of various degrees of quality, depending on the specifications of the various products being manufactured, to be melted down for pouring into molds. Scrap aluminum was sometimes melted, which often included foreign material such as steel wool. The furnace doors were often opened for brief periods during the melting process. The molten aluminum flowed from the furnaces into large vats. When the vats were full, the furnace doors were opened and the vats removed. In general, all six furnaces were not in use at one time; several furnaces often "idled" with the furnace doors open. The turnaround time for each furnace appeared to be roughly the same, thus keeping the overall level of activity generally fairly constant.

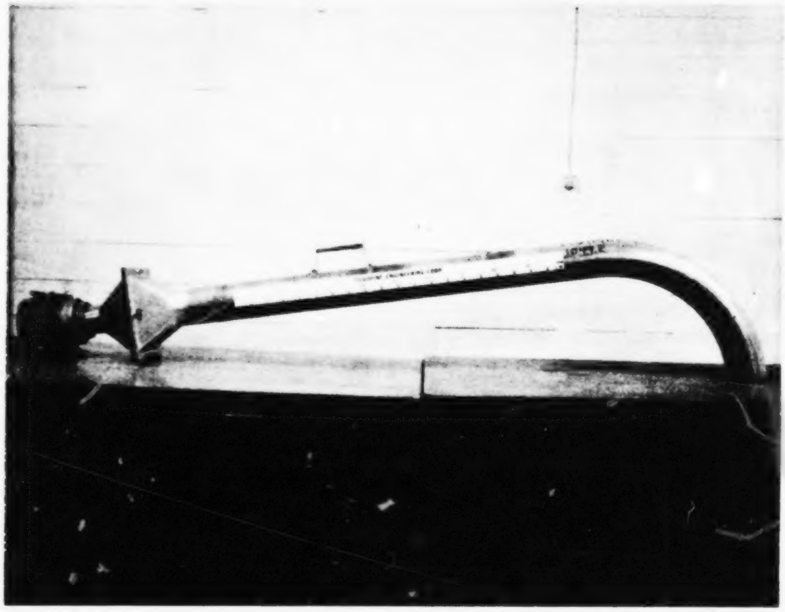


Figure 12. High volume sampler and probe assembly

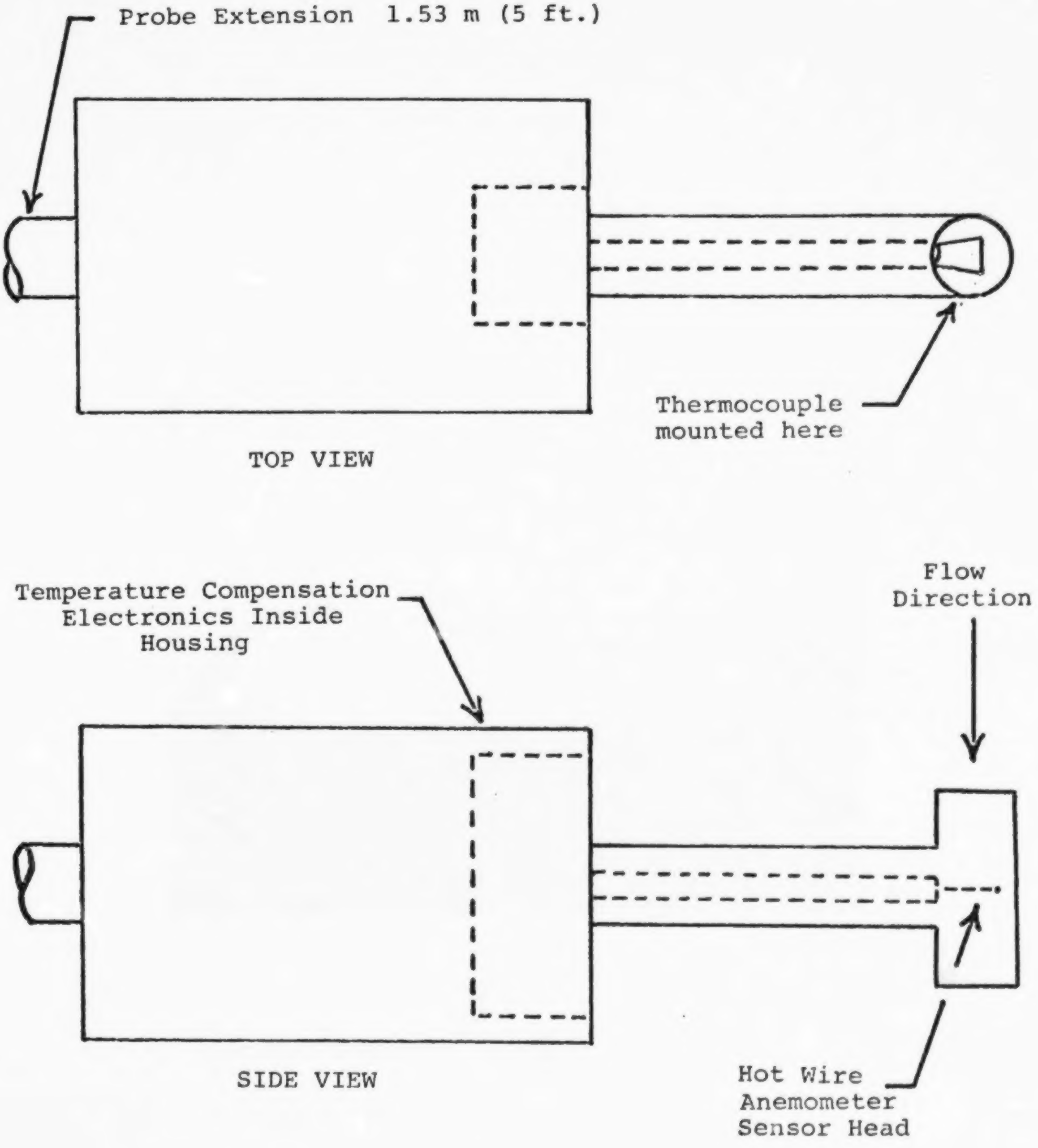
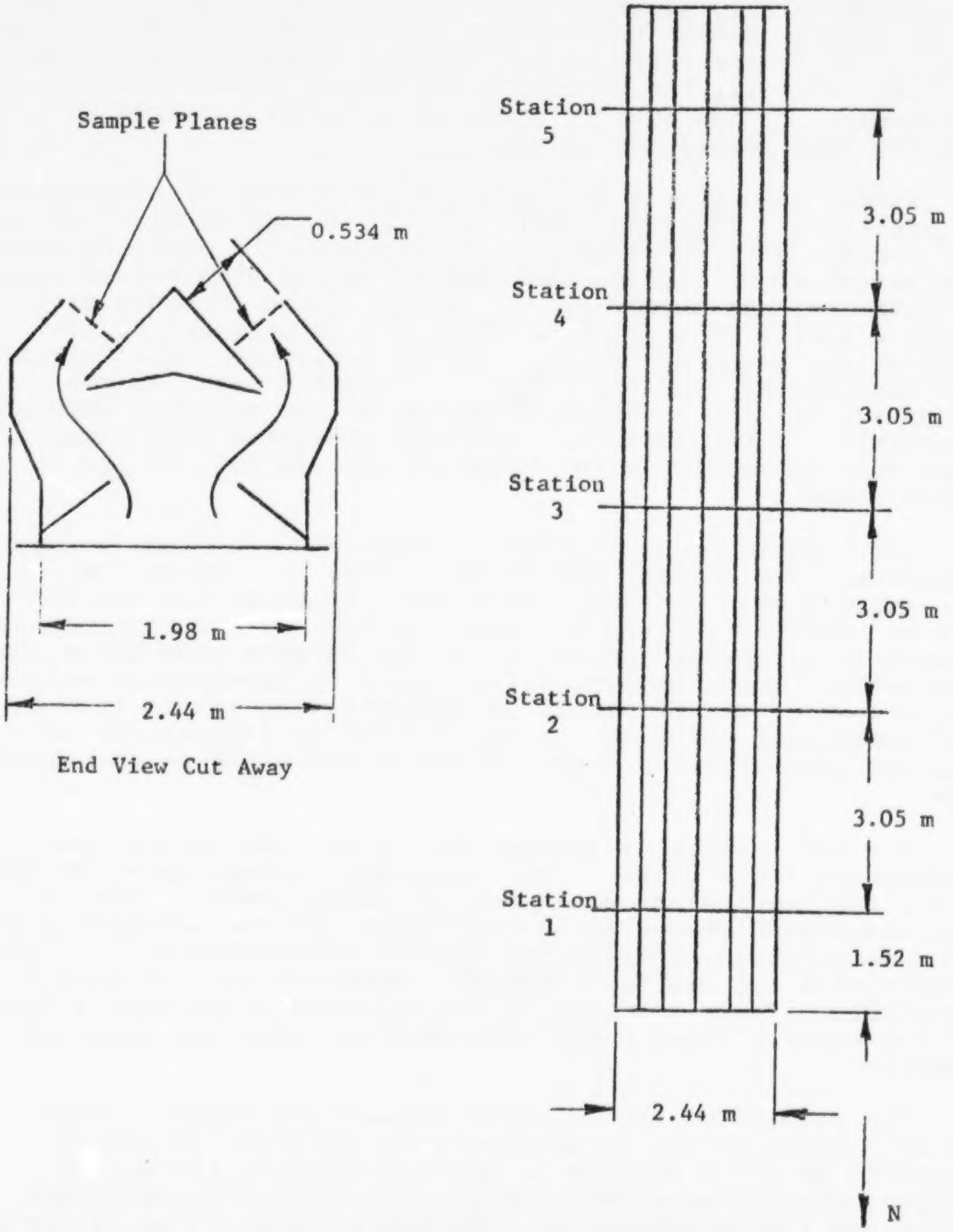

Probe Extension 1.53 m (5 ft.)
Thermocouple mounted here
TOP VIEW
Temperature Compensation Electronics Inside Housing
Flow Direction
SIDE VIEW
Hot Wire Anemometer Sensor Head

Figure 13. Hot wire anemometer and protective collar assembly


End View Cut Away

Sample Planes
0.534 m
1.98 m
2.44 m
Station 5
Station 4
Station 3
Station 2
Station 1
3.05 m
3.05 m
3.05 m
3.05 m
1.52 m
2.44 m
N

Figure 14. Sampling locations for preliminary field tests - Hitchcock Industries roof ventilator

Visual observations of occasional plumes rising from the furnaces indicated that the flow was sometimes very turbulent, becoming well mixed by the time the roof ventilator was reached, and sometimes appeared much more uniform, rising steadily in a single column. In general, it was difficult to characterize the activities within the foundry by specific, scheduled operations, such as the charging and tapping operations described in Ref. 29. Overall, the Hitchcock Industries site provided a good example of the type of problems to be encountered in studying roof ventilator emissions.

Sample planes were chosen for maximum ease of alignment of the particulate sampling probe, as illustrated in Figs. 15 and 16. Samples were extracted for 90 minutes at a constant flow rate indicated by a rotameter mounted on the high volume sampler. The rotameter was calibrated by measuring the pressure drop across a series of orifice metering plates attached to the inlet of the probe nozzle in order to determine the actual flow rate through the sampling probe. Isokinetic sampling was attempted, but the fluctuating nature of the velocity made this impossible. Later review of the data indicated that sampling rates were typically in the range of 150% to 230% of the isokinetic rate.

Particulate concentration measurements obtained during the preliminary field tests are shown in Fig. 17. Since the measurements were extracted at various times during the two days of testing, the results shown in Fig. 17 are representative of several different activities in the furnace room below the ventilator. Thus, these results should be interpreted only as indications of the magnitude of concentration levels in the roof ventilator emission stream, and not as indications of possible concentration gradients which may exist at any given time.

Several velocity traverses were also made during the preliminary field tests. The measurement planes were the same as for the particulate concentration measurements. The hot wire anemometer proved to be unsuitable for the awkward conditions encountered; despite the special protective collar, the fragile wire tip was soon damaged, rendering the instrument inoperable. Thus, the bulk of the velocity measurements during the preliminary field tests were obtained with the vane anemometer.

The results of two velocity surveys are shown in Figs. 18 and 19. Although the velocities shown in Figs. 18 and 19 appear to be quite similar in the two surveys, the actual velocity fluctuated considerably about these plotted values determined from the velocity instruments, and the magnitude of the average velocity differed by a factor of 1.7. Different wind conditions were observed during these two velocity surveys,

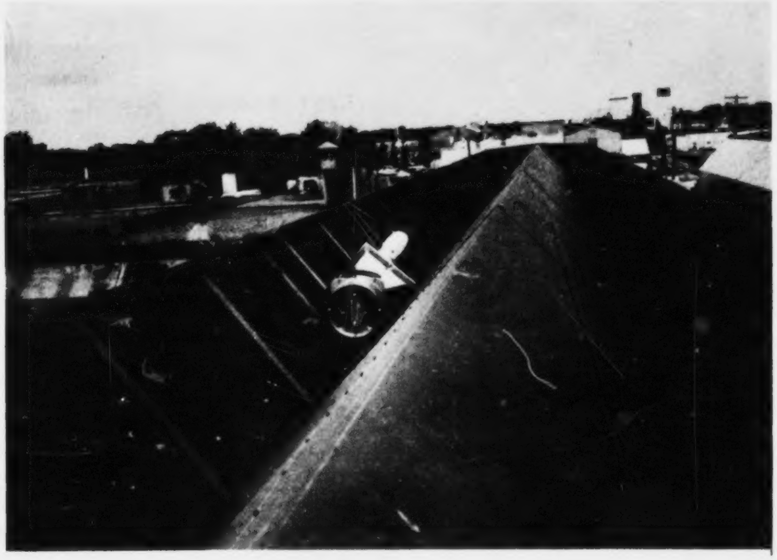


Figure 15. High volume sampler assembly mounted in the roof ventilator at Hitchcock Industries (end view looking north)

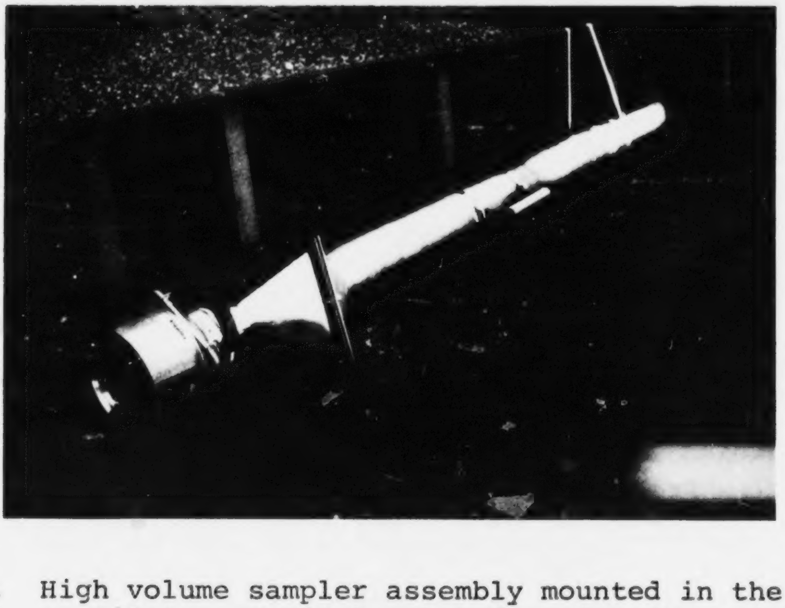


Figure 16. High volume sampler assembly mounted in the roof ventilator at Hitchcock Industries (top view looking down into exhaust region)

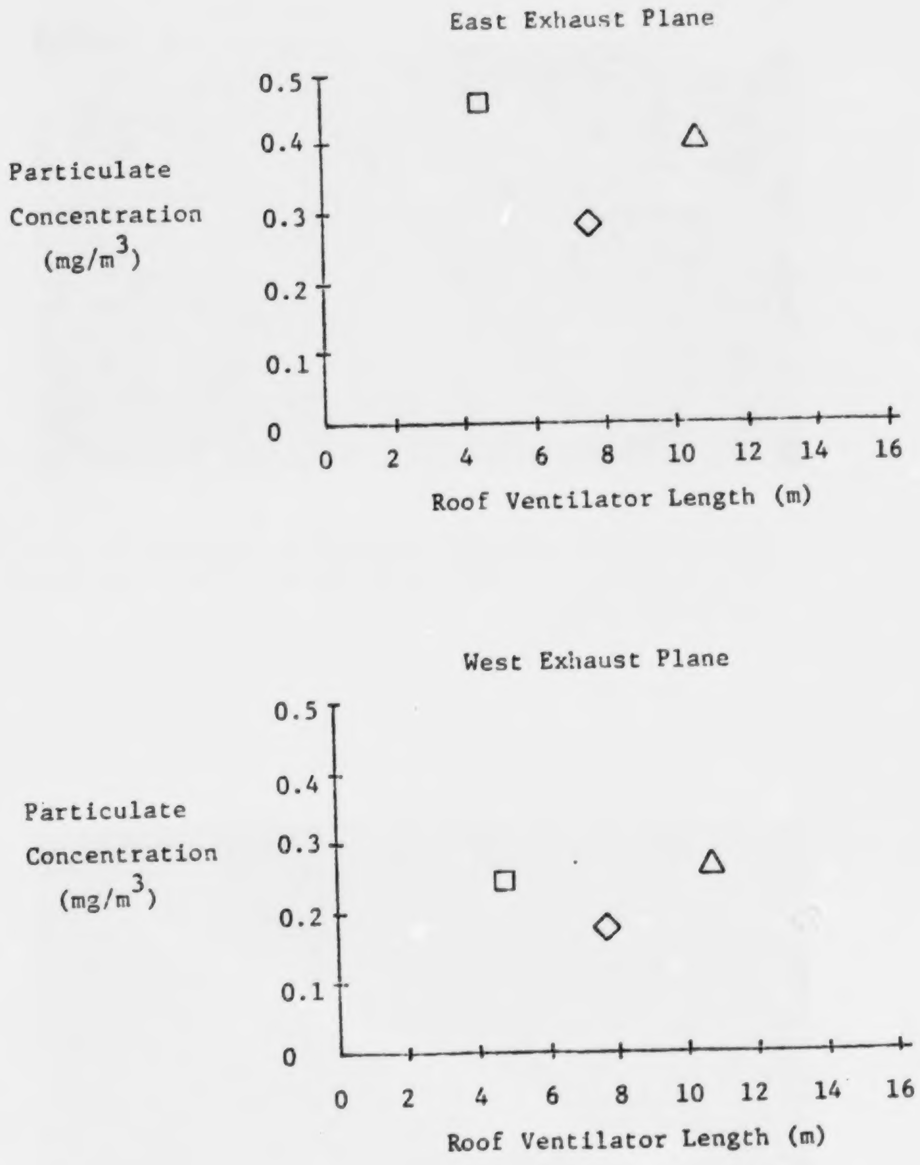


Figure 17. Preliminary field test concentration measurements Hitchcock Industries roof ventilator

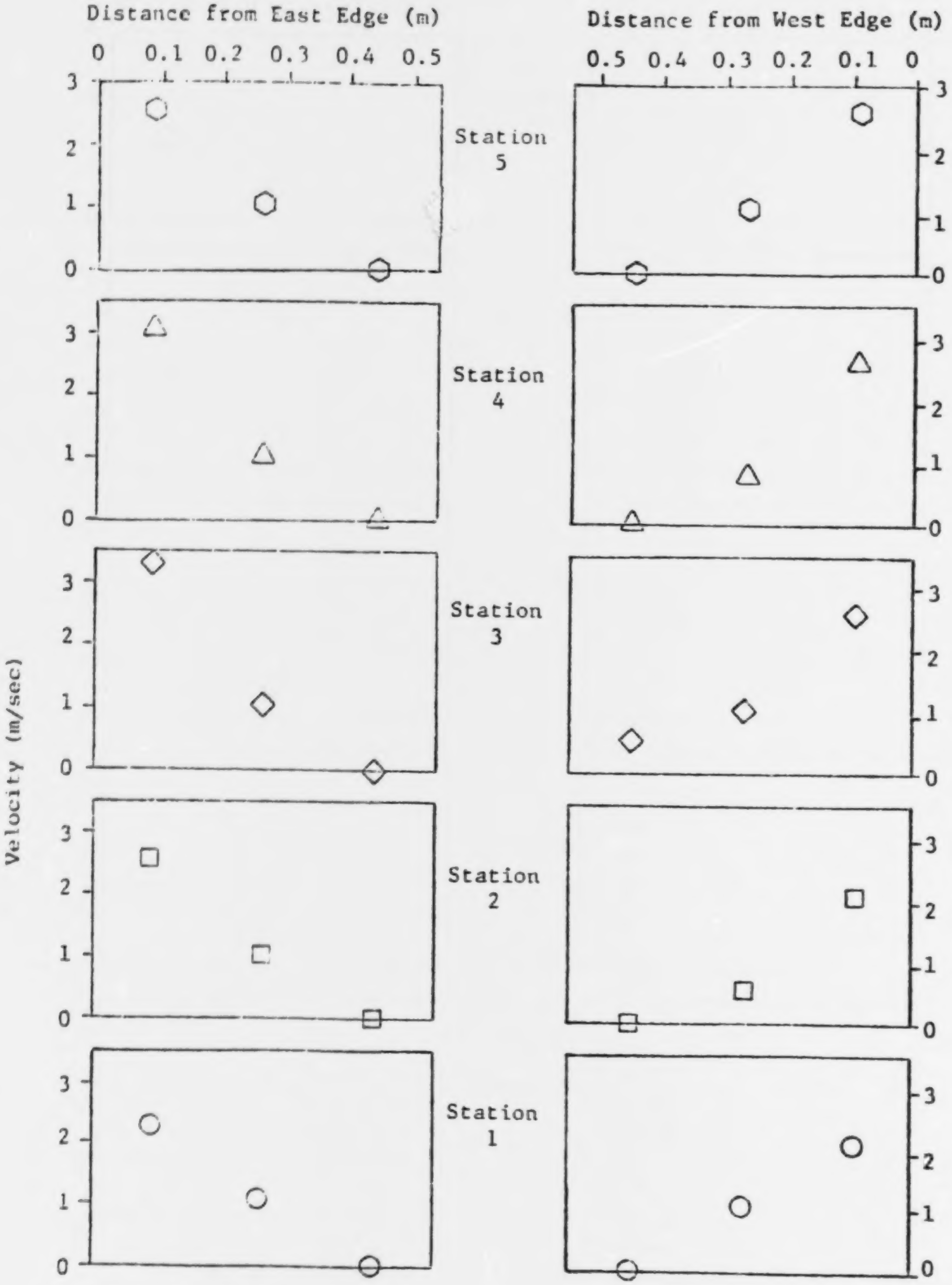


Figure 18. Preliminary field test velocity survey 1, Hitchcock Industries roof ventilator

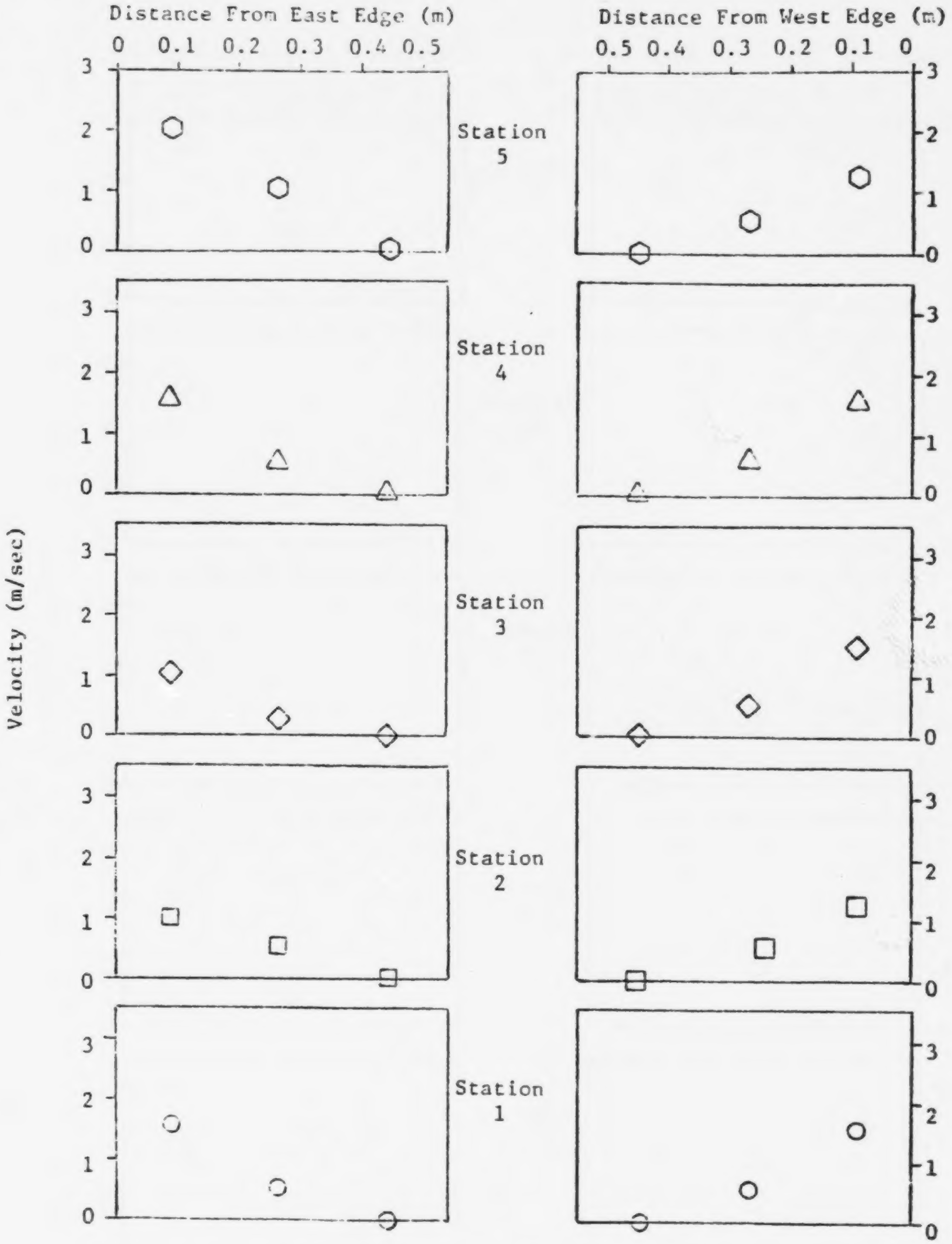


Figure 19. Preliminary field test velocity survey 2 Hitchcock Industries roof ventilator

the component of wind normal to the length of the ventilator being 14 times larger in the case of the larger measured velocities. Other factors which could affect the exhaust velocity are the ambient air temperature and the temperature distribution inside the furnace room, which depends on the particular activities inside the foundry. Therefore, the velocity data shown in Figs. 17 and 18 must also be considered only as an indication of typical magnitudes and not definitive characteristics of the roof ventilator exhaust.

The exhaust stream temperature was also found to vary considerably, ranging from 26°C to 49°C, the average temperature being approximately 34°C. The temperature was seen to vary with time and with position along the roof ventilator, although no attempt at correlation was made.

MODEL STUDIES

The model studies phase of the test program was developed on the basis of these preliminary observations and measurements. A laboratory model representative of a typical roof ventilator was designed and fabricated, and this model was used to evaluate techniques and instrumentation for use in roof ventilator emission measurement.

Model Design and Fabrication

Manufacturer's literature (Ref. 34), and dimensional measurements taken at the Hitchcock site were used to fabricate a model of a section of roof ventilator (Fig. 20). This roof ventilator model was attached to a test section and connected to an existing duct network, used in a previous FluiDyne study at the firm's Rosemount Energy Conversion Laboratory. The model was oriented on the roof in such a way as to maximize the effect of the prevailing wind. The model test facility is shown schematically in Fig. 21 and the roof ventilator model atop the Energy Conversion Laboratory is illustrated in Fig. 22.

In order to provide the capability of introducing particulate matter into the model exhaust, an aerosol generation system was added to the existing ductwork (Fig. 23). The concept of the aerosol generation system was to atomize a weak saline solution by means of a spray nozzle. Heated air then caused evaporation of the water, leaving small particles of salt suspended in the flow stream. The particulate produced by the aerosol generator was estimated to have a mass median diameter in the range of about 1 to 4 μm, varying over this range as the particulate injection mass flow rate was varied to produce different concentration levels in the roof ventilator model. This aerosol generator provided a good simulation of typical particles emitted from a roof ventilator.

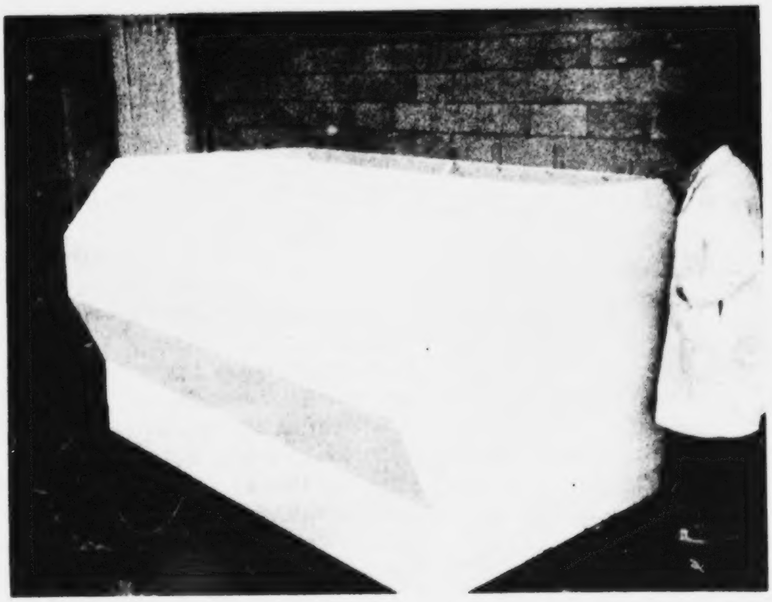


Figure 20. Roof ventilator model

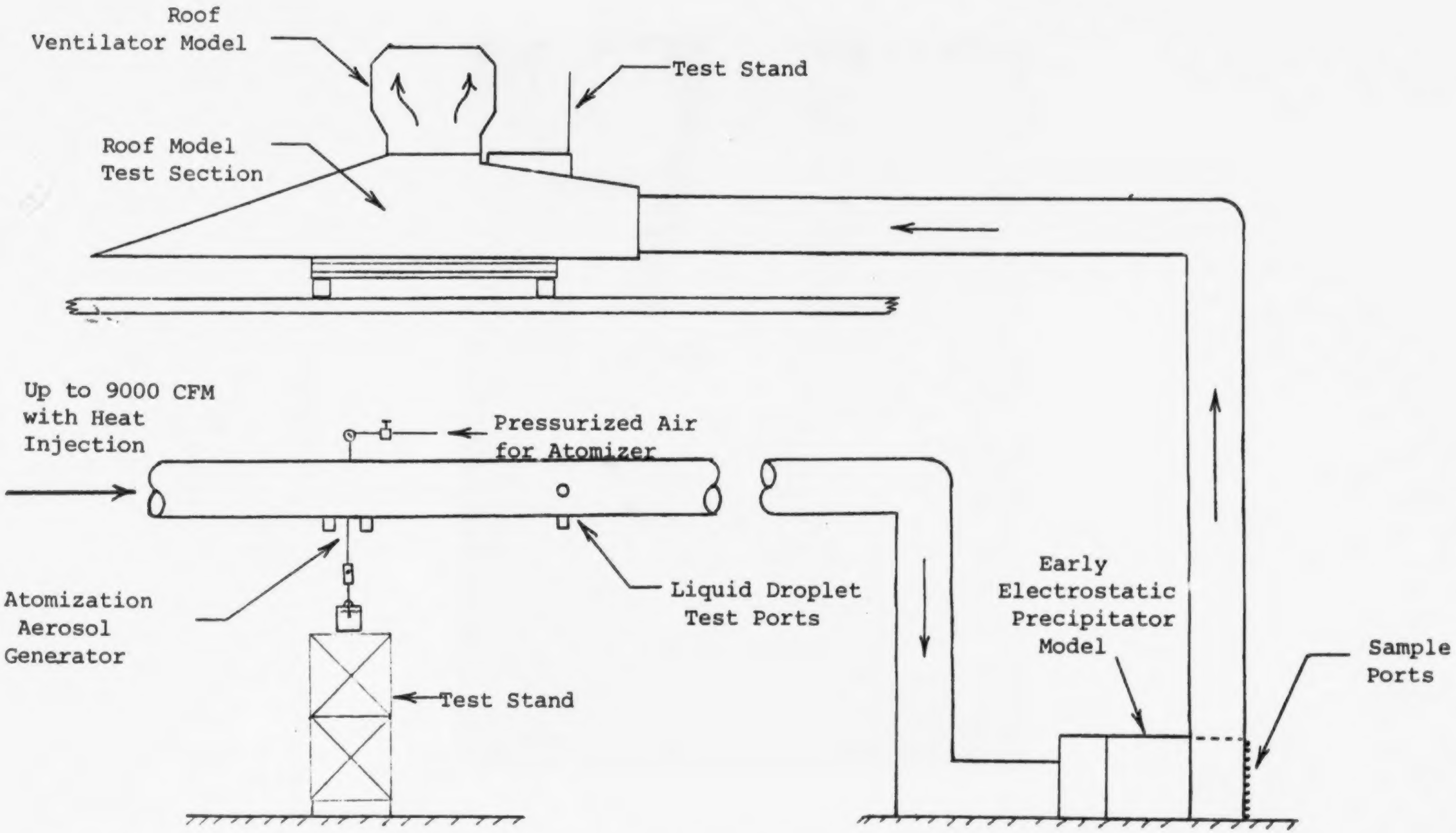

Roof Ventilator Model
Test Stand
Roof Model Test Section
Up to 9000 CFM with Heat Injection
Pressurized Air for Atomizer
Atomization Aerosol Generator
Liquid Droplet Test Ports
Test Stand
Early Electrostatic Precipitator Model
Sample Ports

FIGURE 21. Roof ventilator model test facility - Rosemount Energy Conversion Laboratory

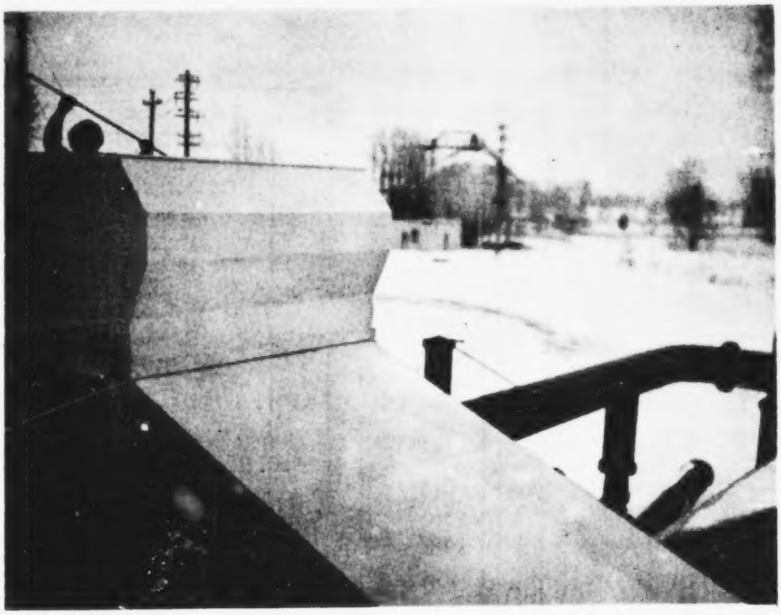


Figure 22. Roof ventilator model test section

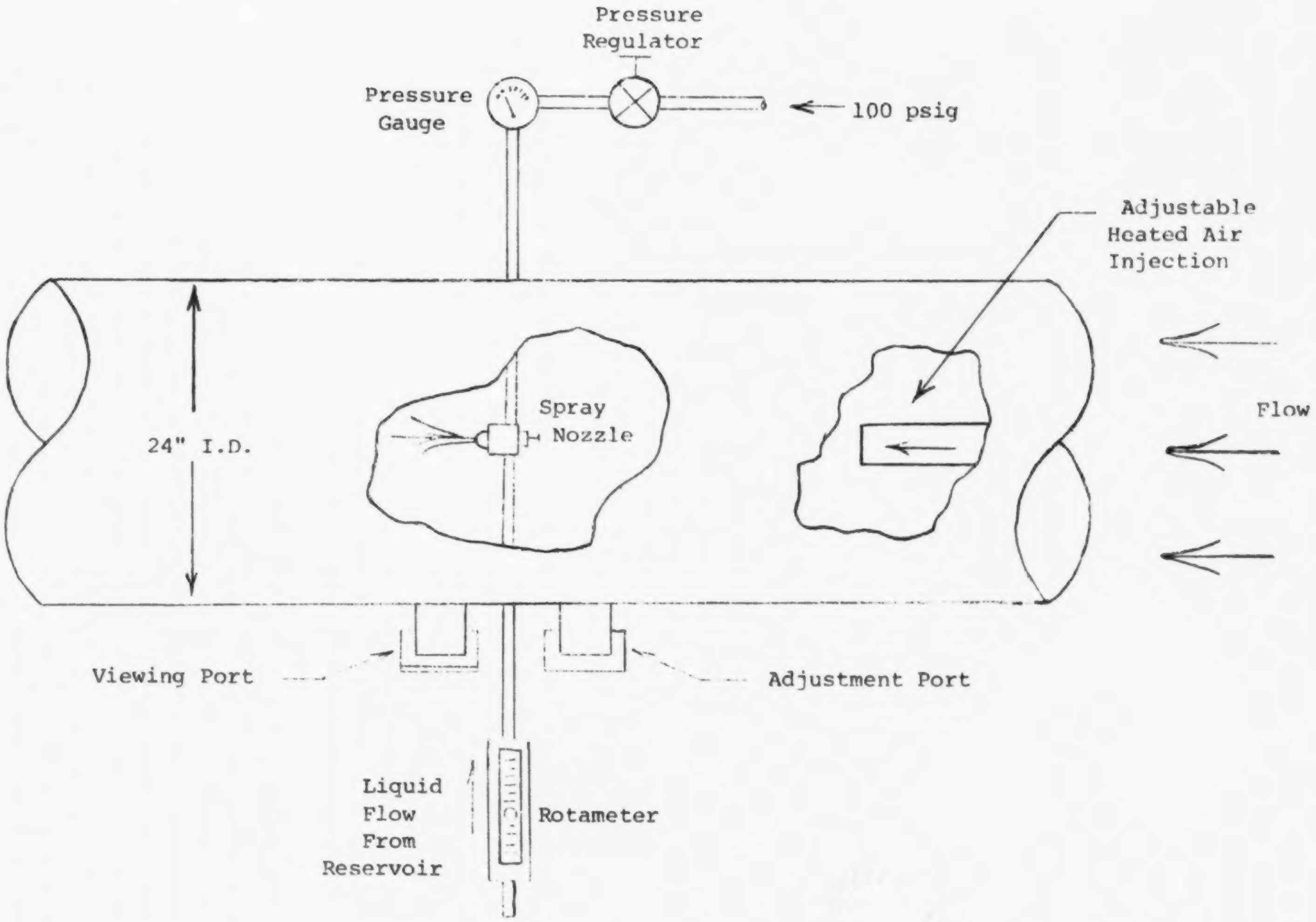

Pressure Regulator
Pressure Gauge
100 psig
Adjustable Heated Air Injection
Flow
24" I.D.
Spray Nozzle
Viewing Port
Adjustment Port
Liquid Flow From Reservoir
Rotameter

Figure 23. Atomization aerosol generator and hot air injection system-Rosemount Energy Conversion Laboratory

Unfortunately, during the course of the roof ventilator model test program, FluiDyne's Energy Conversion Laboratory facility was destroyed by a fire, as was the entire roof ventilator test facility. This necessitated the construction of a second model at FluiDyne's Medicine Lake Laboratory. This model, illustrated in Figs. 24 and 25, followed essentially the same design as the original roof ventilator model. The aerosol generation system for the second roof ventilator model, illustrated in Fig. 26, also followed the same concept and produced similarly sized particles as the original model facility.

Four sample ports were located at the base of the second model (Fig. 27) to allow sampling in a plane at the base of the ventilator as well as in the ventilator exhaust. Testing on both roof ventilator models included flow visualization studies, velocity measurements, and particulate concentration measurements.

Flow and Velocity Studies

The first objective of the model testing program was to evaluate the capability to determine total volumetric flow through the roof ventilator model. Early observations indicated that the exhaust from the model often exhibited very complex flow patterns which could not be readily determined with conventional velocity instrumentation. Therefore, flow visualization studies were conducted using lightweight flow direction tufts as well as smoke injection to examine the fluid motion through the roof ventilator (Figs. 28 and 29).

A circulatory flow pattern, illustrated schematically in Fig. 30, was observed at the ventilator exhaust. The severity of the exit velocity profile as well as the depth in the roof ventilator to which circulatory flow was evident were seen to depend strongly on the atmospheric wind conditions. This fact, together with the inability of conventional velocity instrumentation to give reliable values for total volumetric flow rate, led to the conclusion that velocity measurements should be made in a plane other than the exit from the ventilator.

A plane near the base of the roof ventilator provided a better sampling location. The sample ports shown in Fig. 27 were used to study the flow behavior near the base of the ventilator model. A certain degree of circulatory flow was still evident, but appeared to be of a steady state nature, unaffected by wind gusts and other external disturbances. It was determined that this circulatory flow was caused by the rapid expansion of the test section which supplied the flow to the model (see Figs. 24 and 25) and that insertion of a flow straightening baffle upstream of the model eliminated this circulatory flow near the base of the ventilator. A typical flow profile observed with this flow straightening baffle in

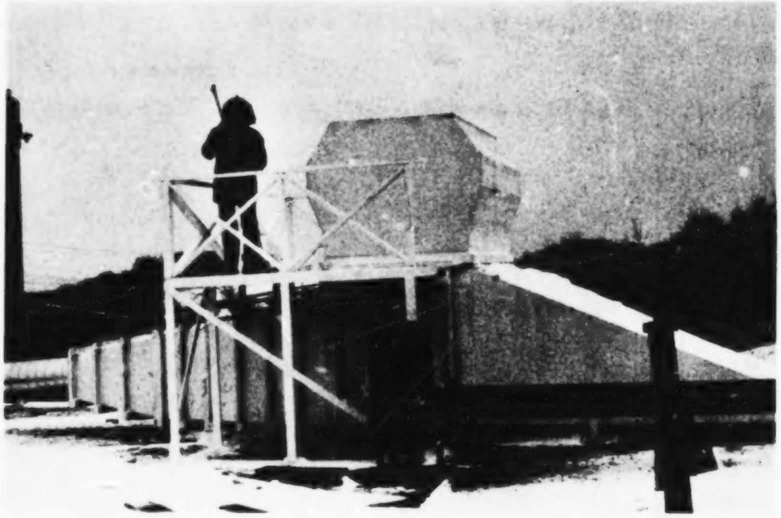


Figure 24. Roof model located at the Medicine Lake Aerodynamic Test Facility - looking south

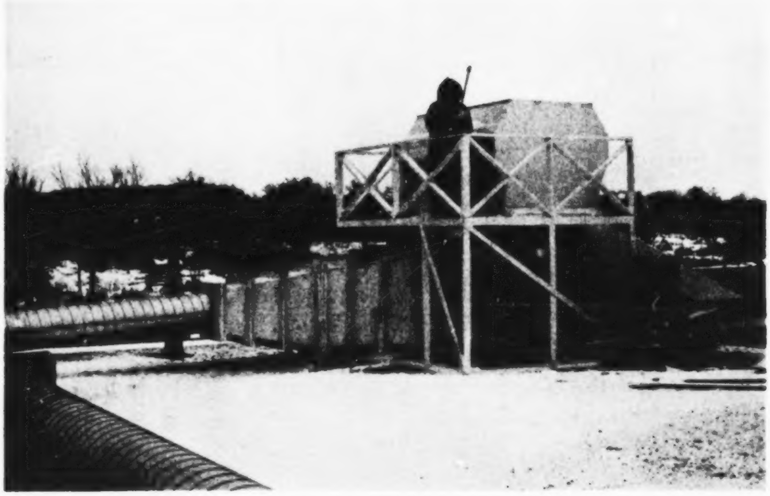


Figure 25. Roof model and ducting located at the Medicine Lake Aerodynamic Test Facility - looking southwest

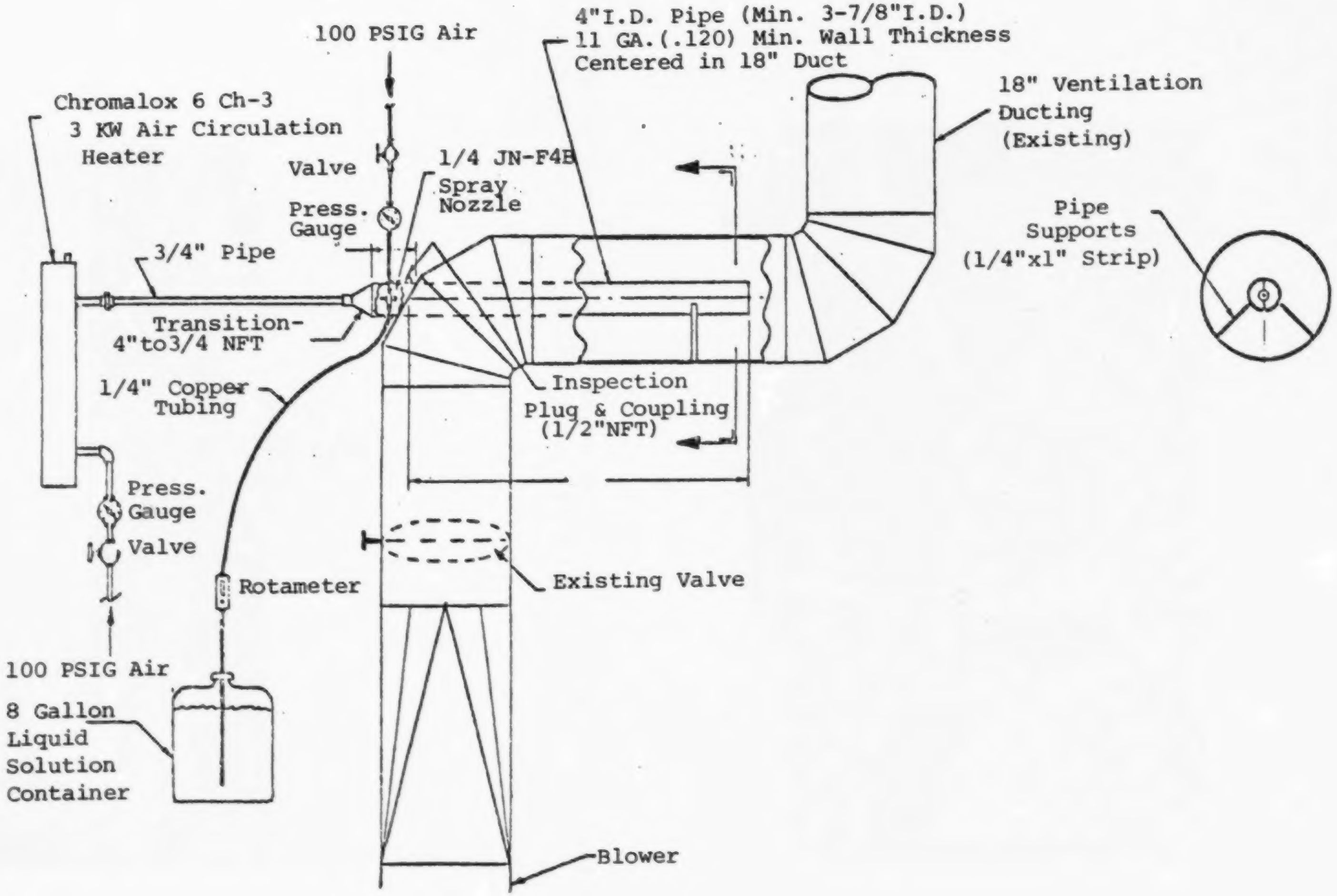

100 PSIG Air
4"I.D. Pipe (Min. 3-7/8"I.D.)
11 GA.(.120) Min. Wall Thickness
Centered in 18" Duct
18" Ventilation
Ducting
(Existing)
Chromalox 6 Ch-3
3 KW Air Circulation
Heater
Valve
1/4 JN-F4B
Spray
Nozzle
Press.
Gauge
3/4" Pipe
Pipe
Supports
(1/4"x1" Strip)
Transition-
4"to3/4 NFT
1/4" Copper
Tubing
Inspection
Plug & Coupling
(1/2"NFT)
Press.
Gauge
Valve
Rotameter
Existing Valve
100 PSIG Air
8 Gallon
Liquid
Solution
Container
Blower

Figure 26. Atomization aerosol generator system with hot air injection - Medicine Lake Aerodynamic Test Facility

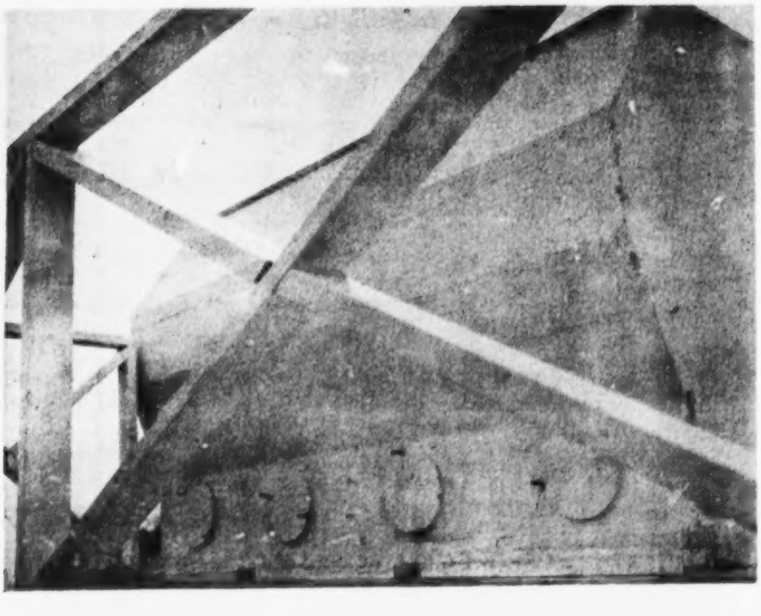


Figure 27. Roof ventilator model sample ports - viewed from northeast

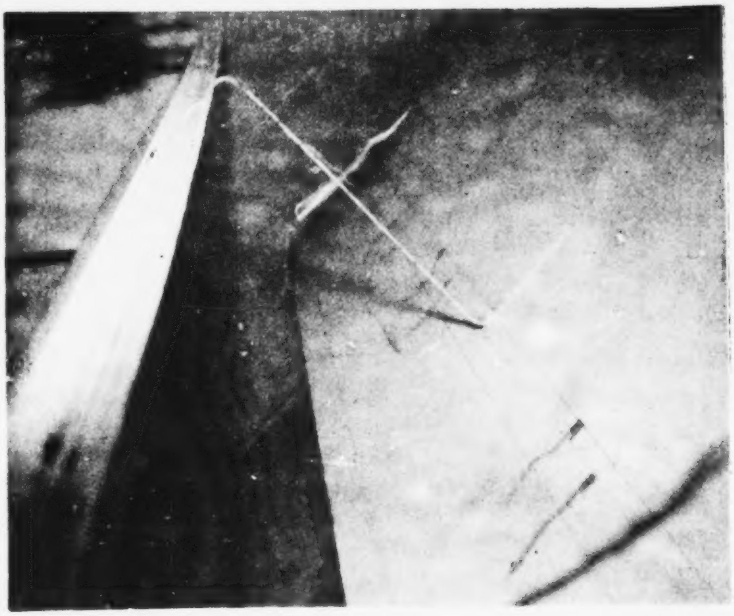


Figure 28. Flow direction indicating tufts in roof ventilator model exhaust

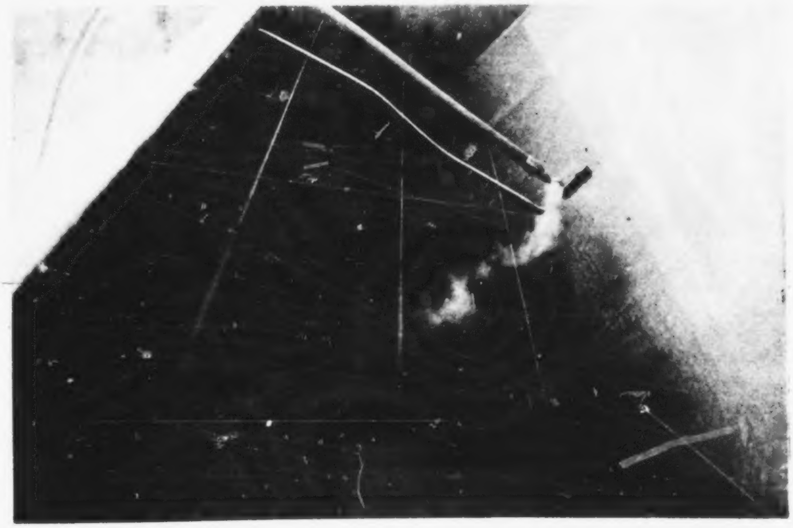


Figure 29. Smoke generator flow indicator in roof ventilator model exhaust

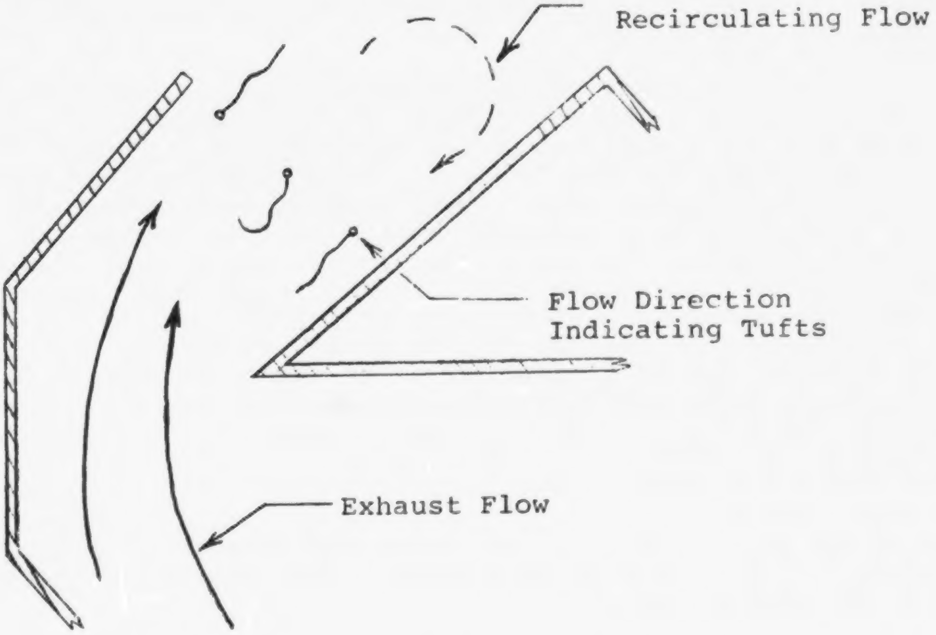

Recirculating Flow
Flow Direction Indicating Tufts
Exhaust Flow

Figure 30. Schematic of observed flow (end view of roof model)

place is illustrated in Fig. 31. A useful feature of this baffle was the capability to produce circulatory flow or uniform flow at the base of the model for the purpose of evaluating the usefulness of various velocity instruments.

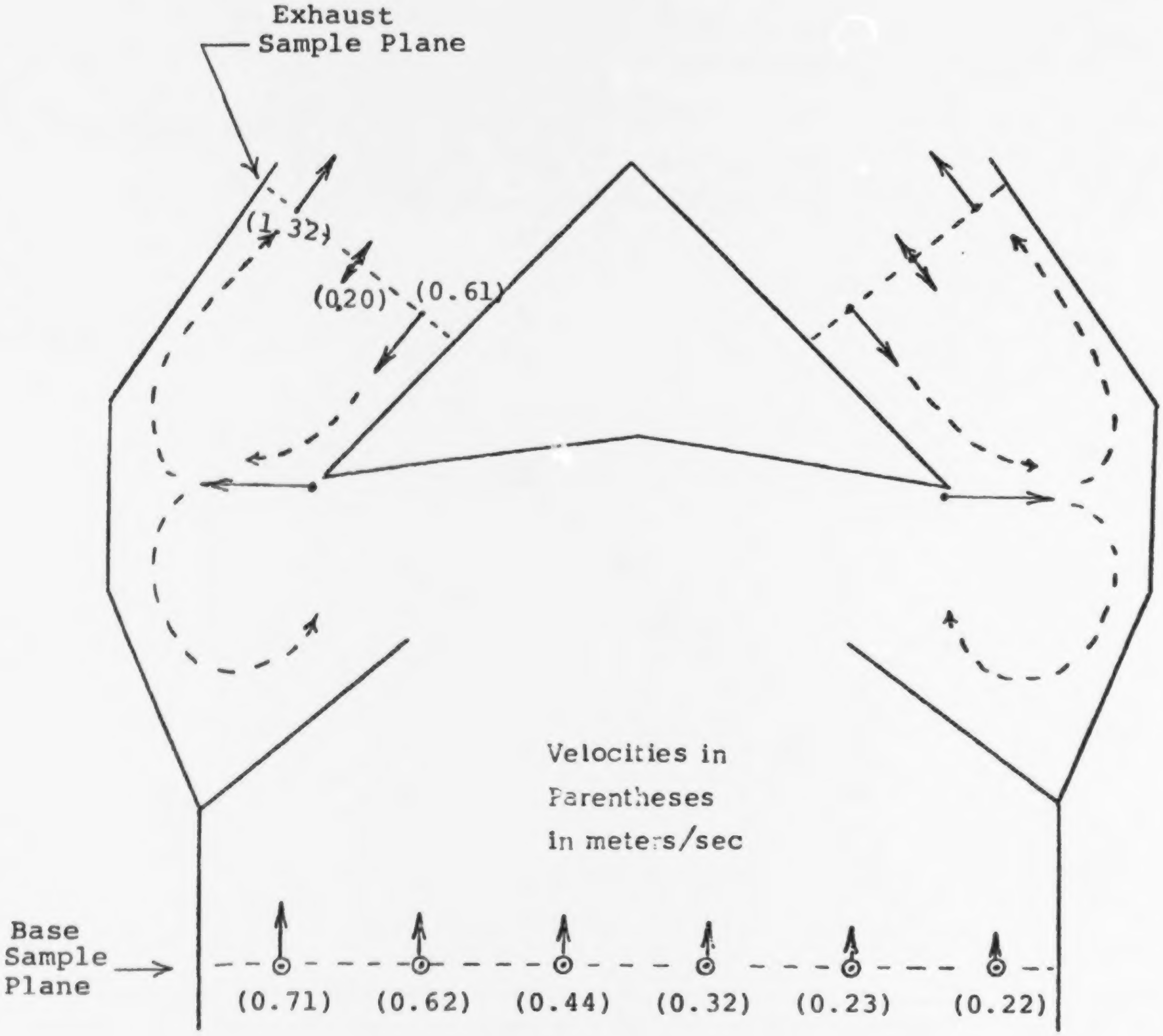
Having established the basic characteristics of the flow through the roof ventilator model, the remaining task was to evaluate the suitability of various commercially available instruments for measurement of the volumetric flow rate. A large number of instruments were considered for this application, and their suitability was evaluated through extensive testing both in the roof ventilator model and at the Hitchcock Industries site.

A detailed description of this evaluation program is given in the Appendix. The description of this program is arranged in the form of a self-contained dissertation entitled "Velocity Instrumentation for Low Velocity, Partially Confined Source Particulate Sampling" due to the general importance and usefulness of this material with regard to the problems of atypical emission sources. To summarize the results of the investigation into velocity instrumentation, it was found that a heated thermopile anemometer, the Hastings-Raydist PCI-30, was capable of accurate determination of the total volumetric flow rate when used at the base sampling plane under two conditions: 1) when the uniform flow baffle was used to provide a non-circulatory flow pattern, and 2) when a secondary observation tool, a lightweight flow direction indicator, was used in conjunction with the instrument in a circulatory flow field with the baffle absent. These results are indicated in Fig. 32. None of the velocity instruments evaluated was capable of providing accurate flow rate data when used at the exhaust plane of the roof ventilator model.

Particulate Concentration Studies

The reliability of particulate concentration measurements using the high volume sampler (Fig. 12) was also evaluated through roof ventilator model studies. The procedure utilized for this evaluation was to introduce particulate matter into the model ductwork by means of the aerosol generation system and attempt to measure the particulate concentration at the roof ventilator model exhaust or at the base of the model through the sample ports. The actual concentration was monitored in the ductwork upstream of the roof ventilator model using EPA Method 5 sampling techniques, collecting particulate matter on 47 mm Gelman Type A glass fiber filters.

The results of these measurements are shown in Fig. 33. The measurements at the exhaust plane consist of single point measurements at various points, while those at the base plane were taken at a single point near the center of the roof



Exhaust
Sample Plane
(1.32)
(0.20)
(0.61)
Velocities in
Parentheses
in meters/sec
Base
Sample
Plane
(0.71)
(0.62)
(0.44)
(0.32)
(0.23)
(0.22)

Figure 31. Typical flow velocities at various points in roof ventilator model

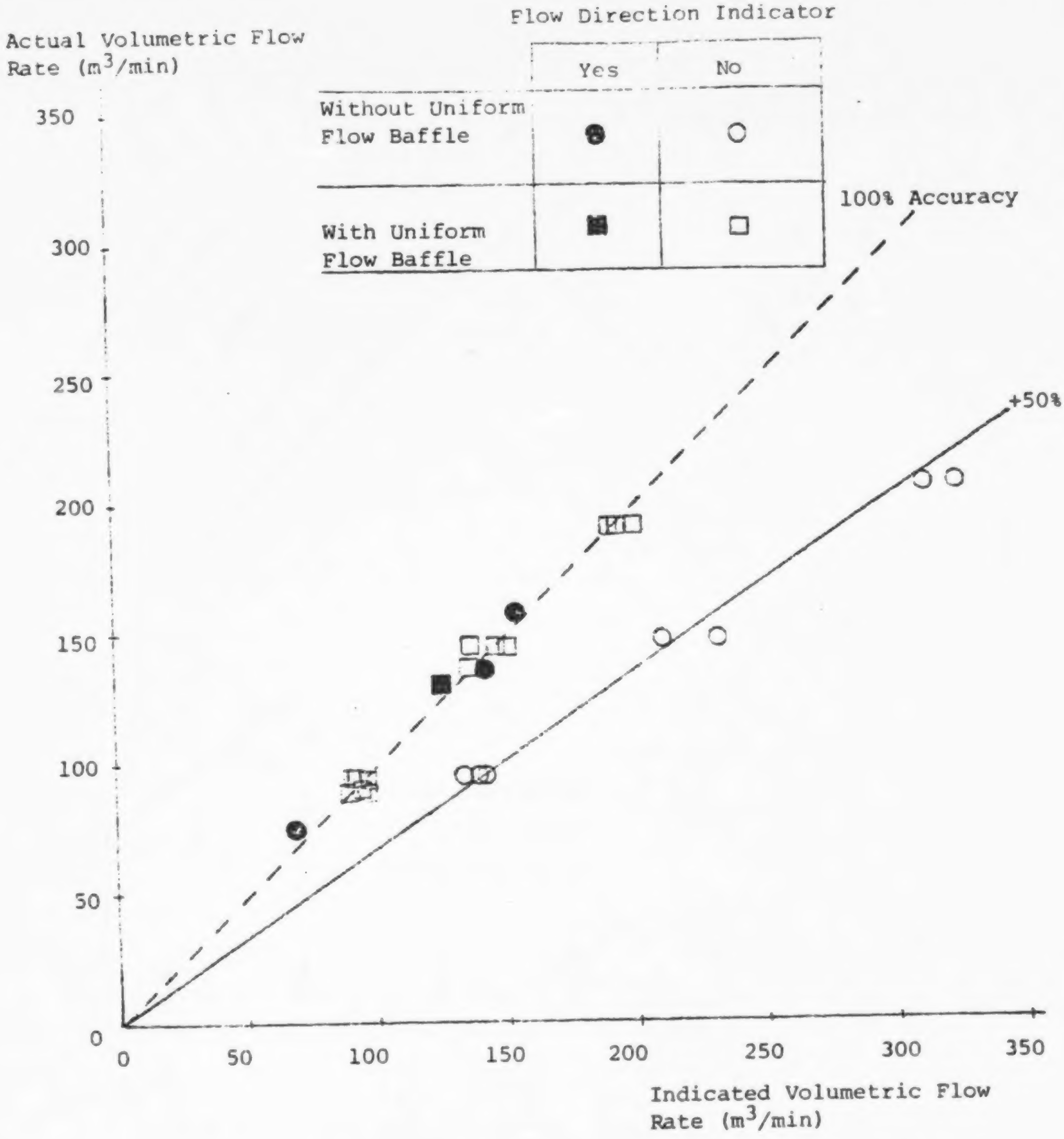


Figure 32. Volumetric flow rate at base of roof ventilator model determined with Hastings-Raydist PCI-30 hot thermopile anemometer

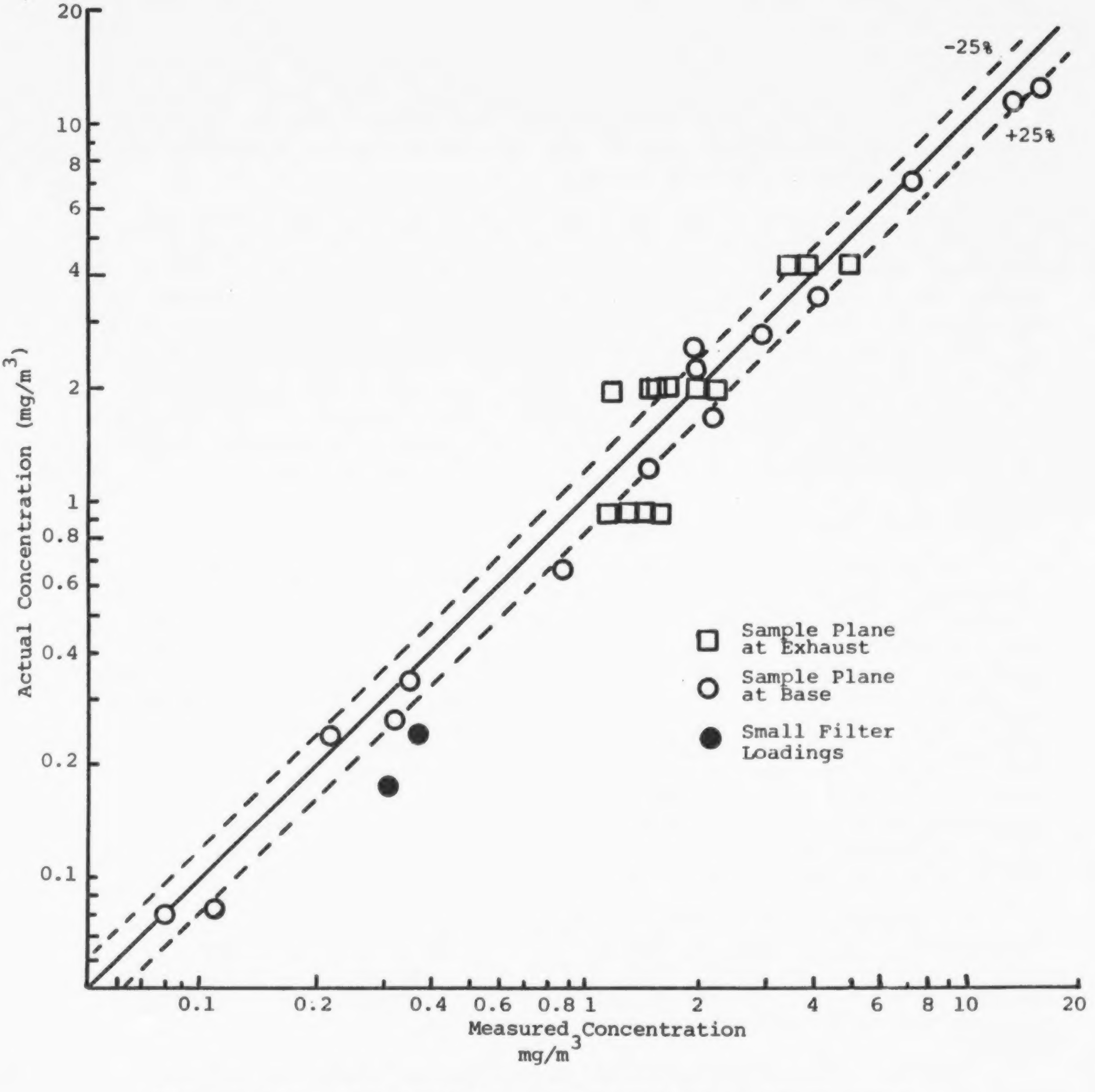


Figure 33. Particulate concentration measurements in roof ventilator model

ventilator model. A great variety of atmospheric conditions was encountered in the course of the particulate concentration testing. Isokinetic sampling with the high volume sample probe was rarely achieved. Sampling rates were typically in the range of 150% to 250% of the isokinetic rate. No obvious correlation was seen between sampling rate or atmospheric conditions and degree of accuracy of the results. This observation is in agreement with Ref. 35, which includes data on the effect of anisokinetic sampling on accuracy of particulate concentration measurements. Using the correlation parameters of Ref. 35 for the injected salt particles, the high volume sampling probe, and the velocity of the model exhaust indicates virtually no detectable error due to anisokinetic sampling over a large range in sampling rates.

The measured particulate concentration is generally seen from Fig. 33 to agree rather poorly with the actual values. However, an overall reliability of ± 25% is indicated over a large range of particulate concentrations for samples taken at the base of the roof ventilator model, with the notable exception of two points near an actual concentration of 0.2 mg/m^3. The accuracy of these two measurements is doubtful, however, since the tests were of insufficient duration and resulted in extremely small loadings on the standard filters. In general, the measurements at the base plane indicate a slightly higher than actual concentration regardless of sample rate.

FINAL FIELD TESTS

In order to evaluate the usefulness of the sampling technique described above under actual field conditions and to examine the effects of the extended length dimension on the roof ventilator problem, which was not possible in the model studies, a final series of field tests was carried out at the Hitchcock Industries site over a five day period. Five sample ports were installed near the base of the roof ventilator pictured in Fig. 10 during a scheduled shutdown of plant activities. The ports were located at the midpoints of five equal area sections of the ventilator, i.e., at locations corresponding to Stations 1-5 shown in Fig. 14. These sample ports provided access to the more favorable sampling plane identified by the model studies, as shown in Fig. 34.

Measurements of particulate concentration, velocity, and temperature were made using the high volume sample probe, the heated thermopile anemometer and a calibrated iron-constantan thermocouple, all inserted into the roof ventilator effluent stream through the sample ports (Fig. 34).

Particulate concentration measurements were conducted throughout each day of testing. A total of five 1.5 hour samples (except one test which was concluded after only 45

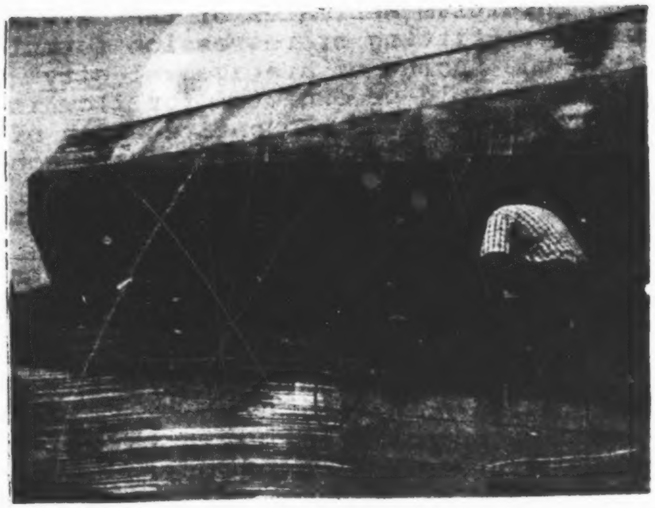


Figure 34. Particulate concentration and velocity measurements at base of Hitchcock Industries roof ventilator

minutes at the first sample port) were taken at each of the five sample ports in the hope that the data would provide insight into the timewise and lengthwise variations of particulate concentration and provide a basis for evaluating the sampling technique with respect to applicability to other extended dimension emission sources.

Velocity measurements were made at various times during each day. During all five days of testing, the flow was observed to be directed relatively uniformly upward, as indicated by a lightweight flow direction tuft, in contrast to the supposed occasional circulatory flow based on visual observations of rising plumes from inside the foundry. Velocity surveys including measurements at all five sample ports were possible before and after the concentration measurements, but only four sample ports were used for velocity surveys during the concentration measurements since the sample probe and velocity probe could not be inserted through the sample ports simultaneously.

The measurements made during the final field tests are summarized in Figs. 35 through 39. The average velocity at each sample port, determined from a six-point widthwise velocity survey, and the particulate concentration are plotted vs. the time of day at which each measurement was made. All five days of field testing are compressed onto a single scale, representing the normal work day, and each data point is identified as to the day it was taken.

Several observations can be made from the roof ventilator measurements shown in Figs. 35 through 39. The average velocity at a given sampling station often varied considerably with time on a given day and also varied from day to day at a given time. General trends can be seen, however. The curves shown on these figures represent intuitive estimates of the "average" data and are not based on curve-fitting or regression formulas. It should be emphasized that the "point of average velocity" was not the same in all cases, as would be expected for flow in a pipe or duct, but was seen to vary over the entire width of the roof ventilator as the various velocity surveys were conducted.

The particulate concentration also varied during each day of testing. In general, concentration levels were seen to be higher near the midpoint of the roof ventilator than at the ends. Since the concentration measurements at each sample location were conducted on different days, it cannot be definitely determined that this variation is due to the position along the ventilator. However, observations of the foundry activities from day to day revealed no obvious procedural differences which would explain overall concentration variations of the magnitude observed in these measurements. Therefore, the observed variations of concentration with position in the

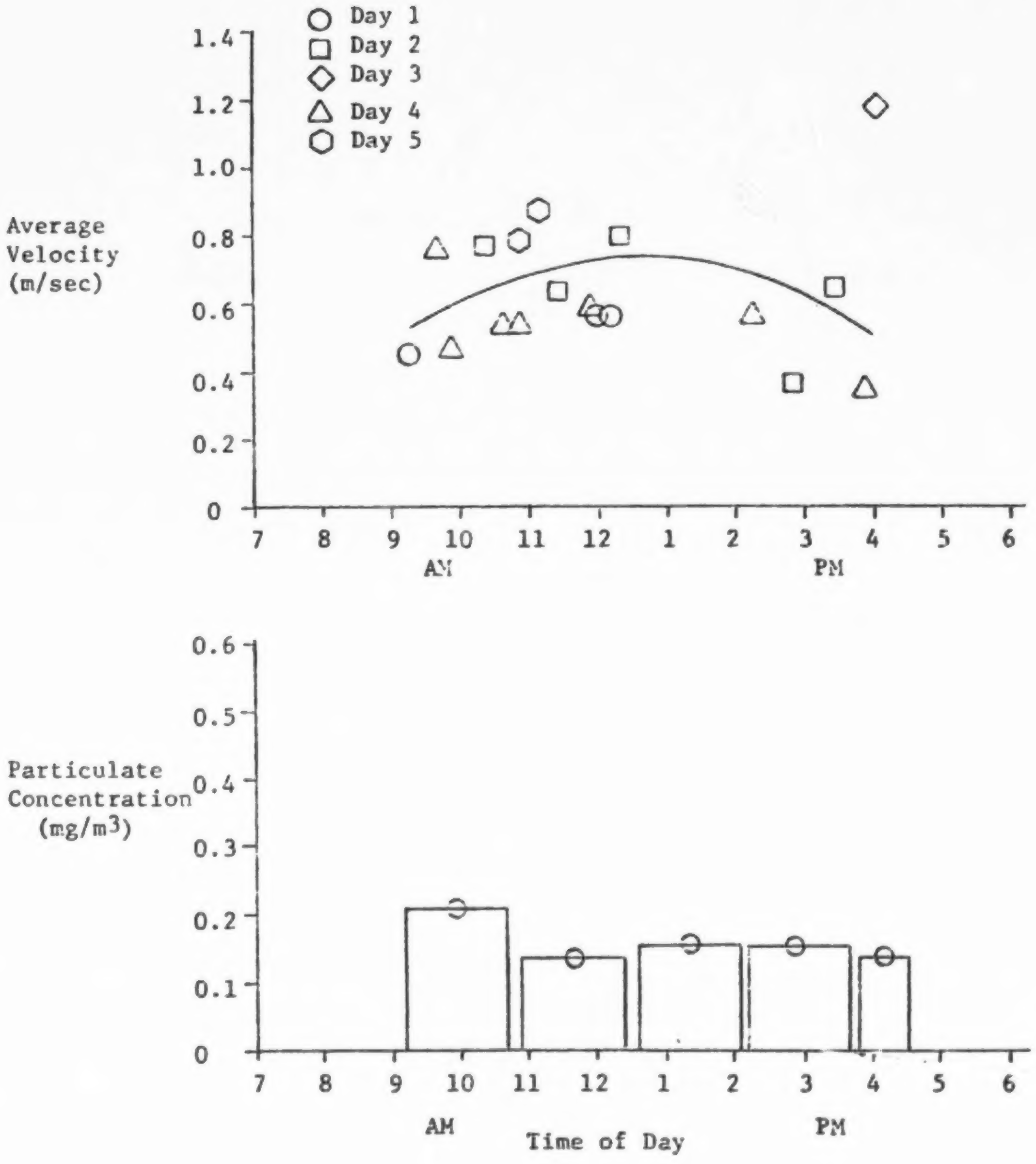


Figure 35. Average velocity and particulate concentration measurements - Sample Port 1 - Hitchcock Industries roof ventilation

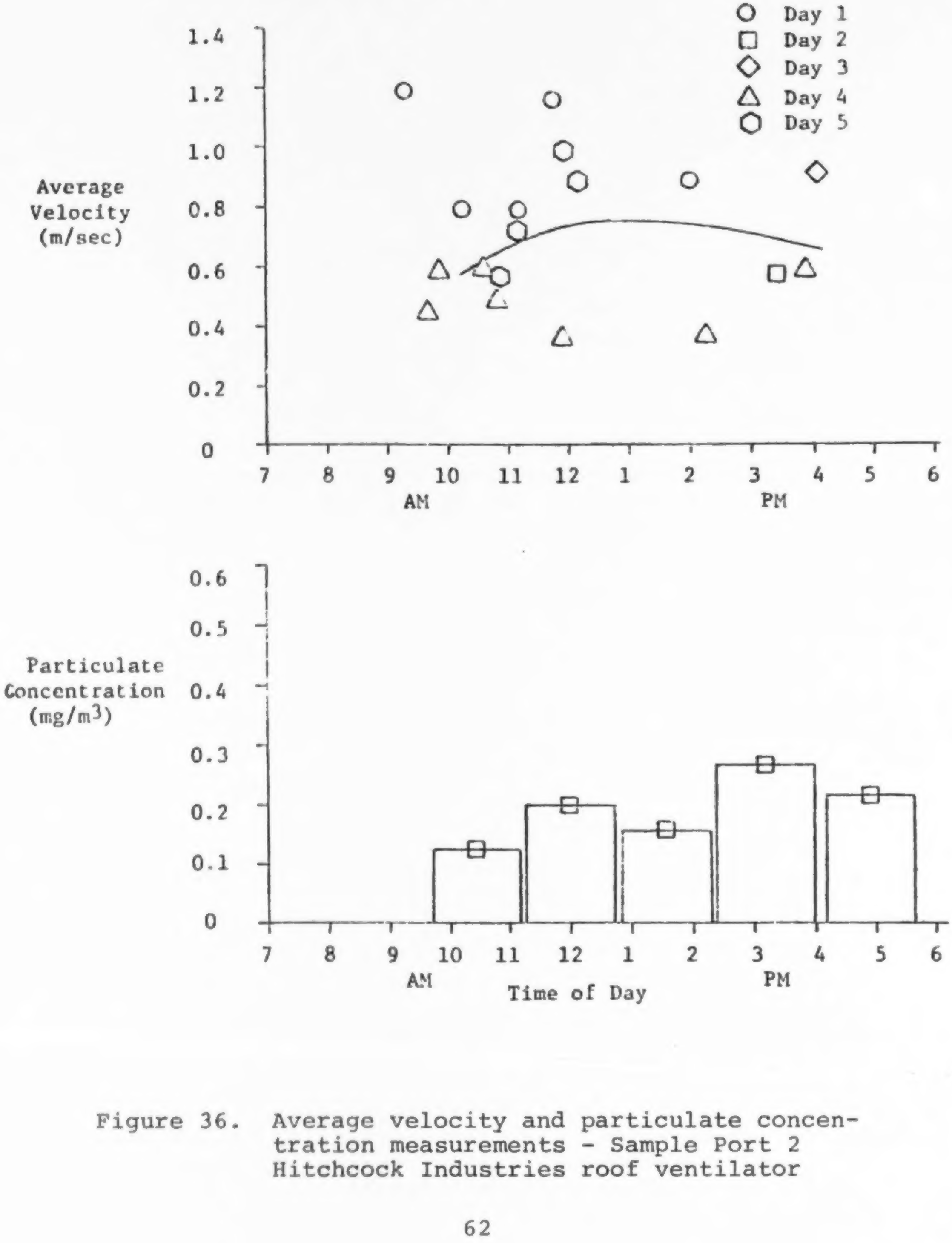


Figure 36. Average velocity and particulate concentration measurements - Sample Port 2 Hitchcock Industries roof ventilator

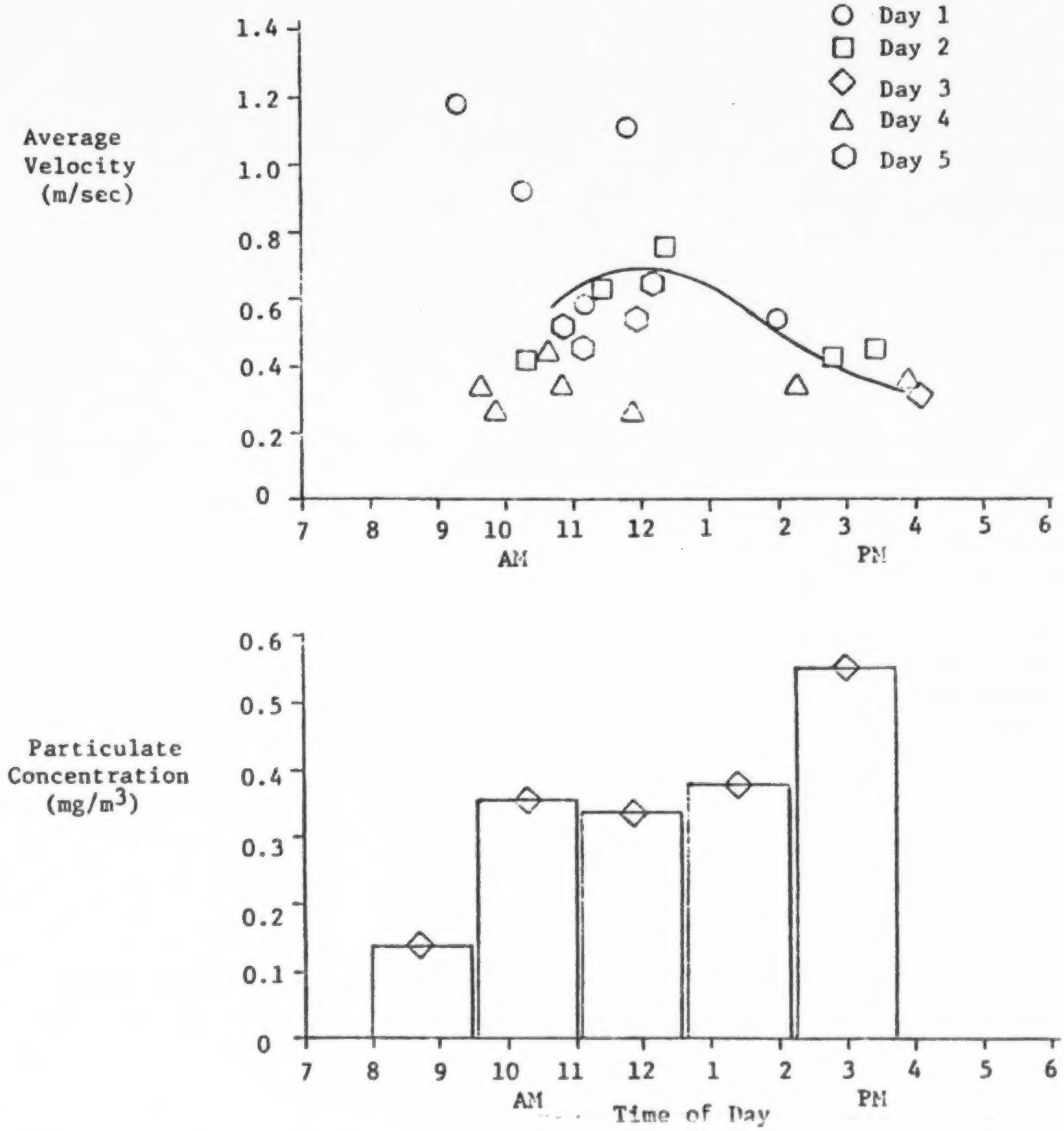


Figure 37. Average velocity and particulate concentration measurements - Sample Port 3 Hitchcock Industries roof ventilator

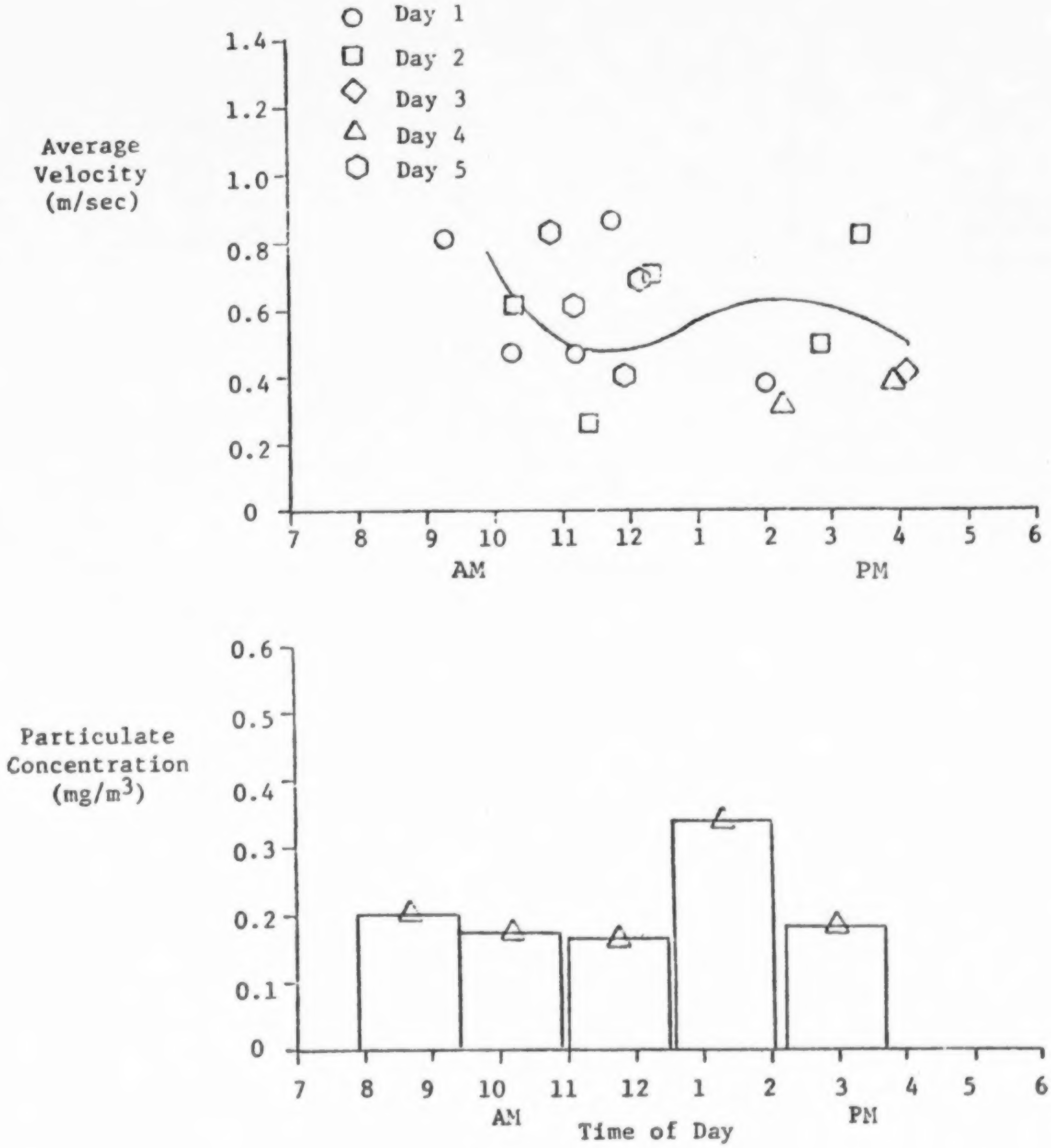


Figure 38. Average velocity and particulate concentration measurements - Sample Port 4 Hitchcock Industries roof ventilator

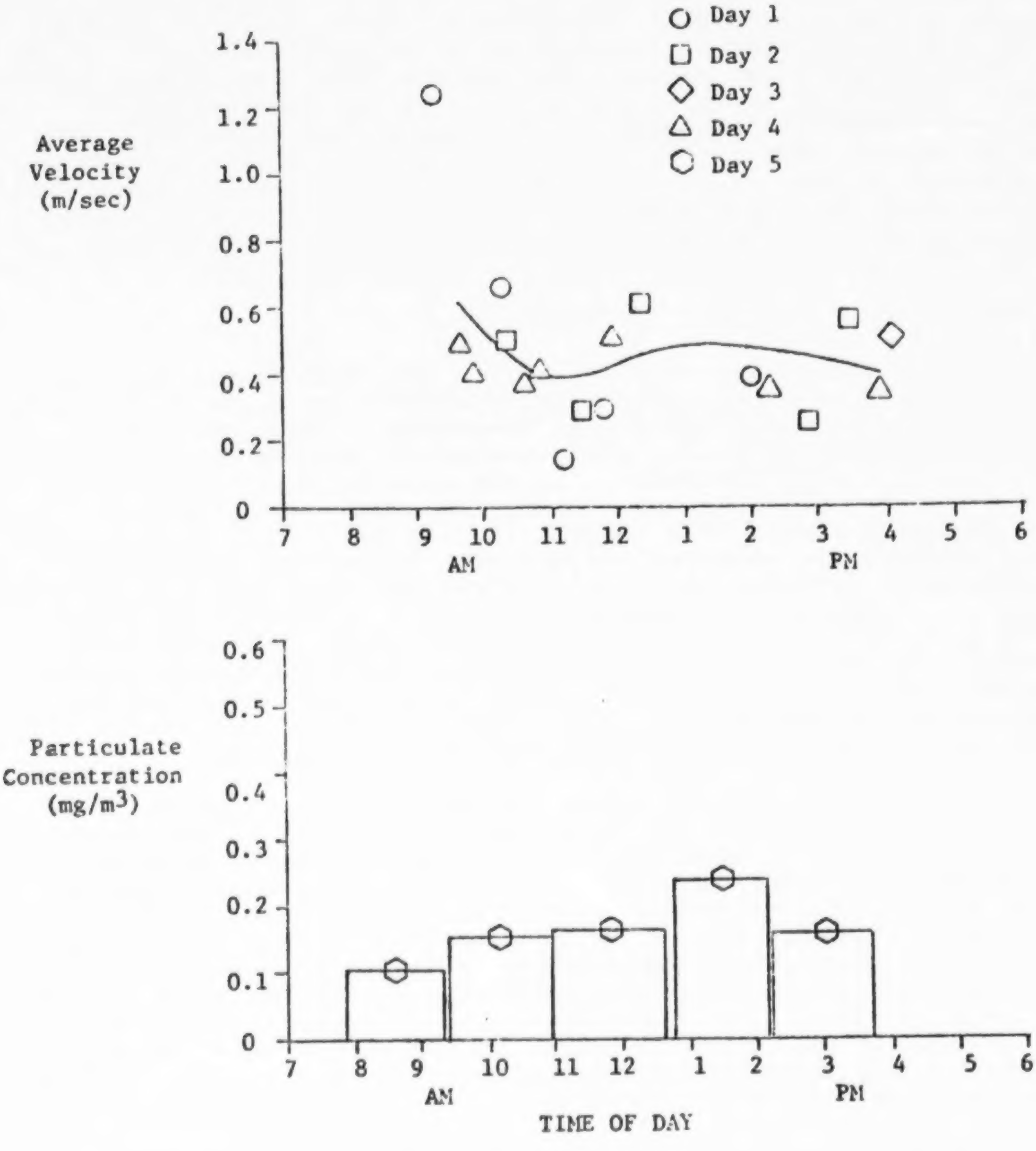


Figure 39. Average velocity and particulage concentration measurements - Sample Port 5 Hitchcock Industries roof ventilator

roof ventilator are assumed to be indicative of the actual situation.

Investigations into a possible relationship between the effluent stream temperature and the velocity and/or concentration indicated no useful correlation. Since the flow through the roof ventilator is governed by a complex interaction of the inside temperature, outside temperature, wind conditions, and many other factors, this observation is not surprising. Often, higher temperatures accompanied higher velocities, but this was not always the case. The temperature occasionally appeared to vary cyclically over a period of several hours, but more often appeared quite random both with time and position, ranging between 35°C and 78°C over the five day test period. The average temperature was on the order of 55°C.

EVALUATION OF SAMPLING TECHNIQUE

The information obtained during the roof ventilator test program led to several conclusions concerning basic measurement techniques for roof ventilator emissions. The complex flow patterns observed at the roof ventilator exhaust dictate the choice of a sampling plane near the base of the roof ventilator, where the velocity is more uniform and less susceptible to atmospheric winds. The volumetric flow rate studies showed that transverse velocity surveys with the heated thermopile anemometer provided very good indications (within ± 10%) of the total volumetric flow rate through the roof ventilator model. The particulate concentration studies in the roof ventilator model indicated that measurements with the high volume sample probe, while lacking a high degree of accuracy, provided reasonable, estimates (typically within ± 25% as seen in Fig. 33) of actual concentration regardless of sampling rate.

These observations defined a sampling technique and a degree of reliability for emission measurements in the model section of a roof ventilator. The questions which remained unanswered concern the number of sampling locations required for a given full-size roof ventilator. The choice of five sampling stations for the 15.24 m roof ventilator studied in the final field tests was based on a desire to obtain the maximum amount of information possible within the scope of the present project. For maximum reliability, particulate samples and velocity measurements should be obtained simultaneously and continuously at all sampling stations throughout the period of emission measurement.

A test program of this magnitude on a roof ventilator in the primary aluminum industry, for example, where ventilators may often be 200 m or more in length, would encounter serious problems with regard to economic feasibility. Thus, the number of sample stations required in a given application is of vital importance. The single application of a secondary aluminum foundry furnace room roof ventilator, studied under the present program, cannot be expected to provide the solution to this problem, since the type of flow and range of particulate concentration is heavily dependent on the particular activity which generates the emissions. In other words, the number of sample stations required for any specific application will undoubtedly depend on characteristics of that application and must be determined for each individual case.

The long sampling time required in order to obtain a weighable collection of particulate matter tends to preclude the use of widthwise particulate concentration traverses at each selected sampling station. Single point concentration measurements were, therefore, chosen on the basis of practicality. Widthwise velocity surveys, however, may be made with considerably less difficulty. In order to demonstrate the importance of the number of points chosen for a widthwise velocity survey, an example based on field test measurements was considered.

A typical velocity distribution, measured at approximately 3:30 p.m. on the second day of final field testing, was analyzed (see Fig. 40). The average velocity which would have been determined from 1, 2, 4, and 5 point widthwise surveys of the velocity distribution shown in Fig. 40 was computed at each sample station and compared with the average velocity from the 6 point surveys actually made during the field tests. The results of this comparison are shown in Table 10. For this particular velocity distribution, it can be seen that at least 4 or 5 point surveys are required to determine the average velocity at each station to within ± 10%. It must be emphasized that, while this velocity distribution is typical of those observed throughout the field test period, not only the average velocity but also the points of average velocity continuously varied with time as the basic velocity distribution varied with atmospheric conditions and activities within the foundry.

As an illustration of the importance of the number of sampling stations for total emission measurements, a second example based on the final field test measurements may be of value. Consider a six-hour period, from 10:00 a.m. to 4:00 p.m., of emission from the 15.24 m roof ventilator. Based on the field test data, typical particulate concentration and average velocity profiles can be constructed as shown in Figs. 41 and 42 for three time instants during this six hour interval. It must be emphasized that these profiles were constructed from data taken over a five day period. The profiles shown in Figs. 41 and 42 are intended to represent a typical example only and should not be construed as actual emission measurements during a single six hour period.

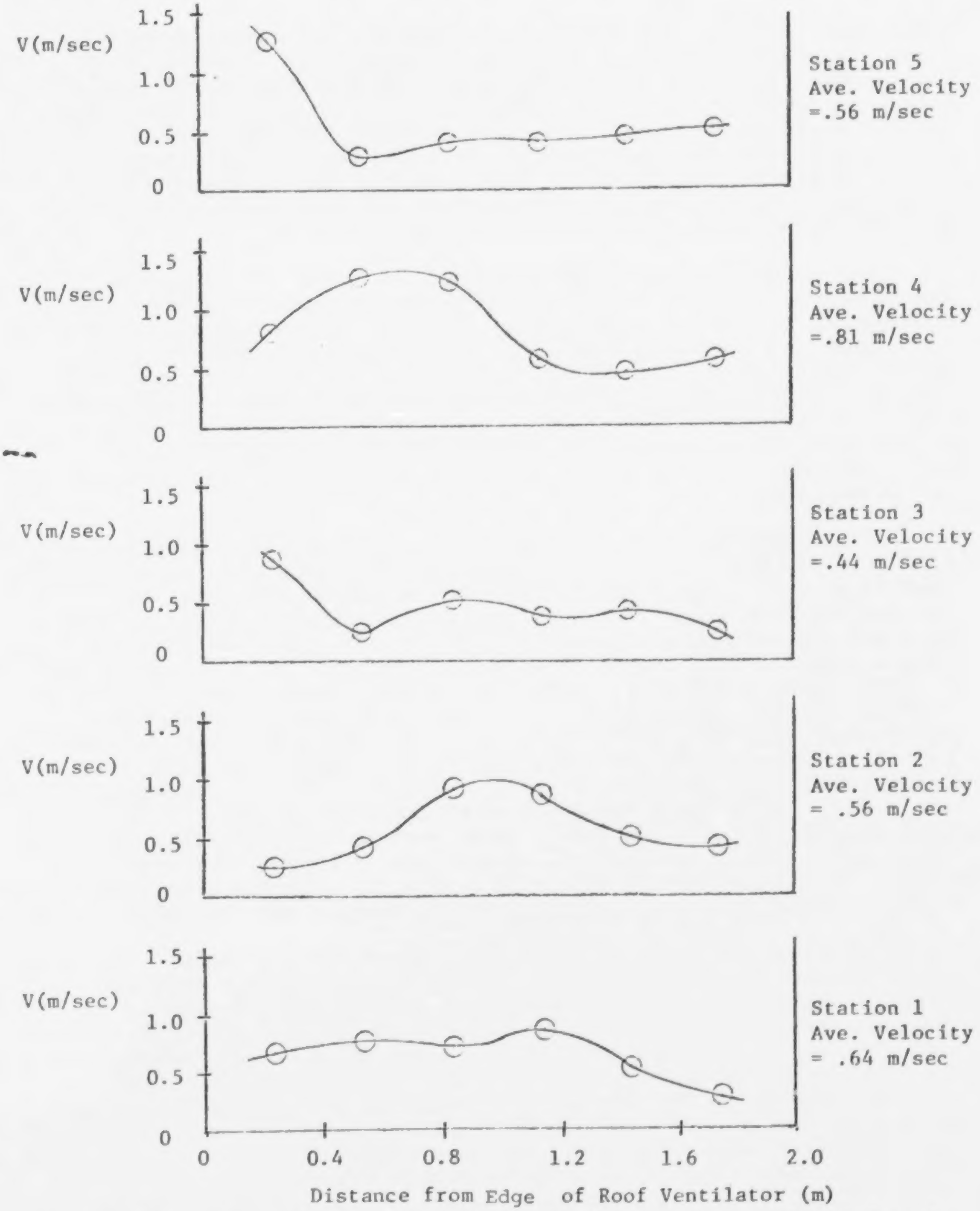


Figure 40. Typical velocity distribution at base of Hitchcock Industries roof ventilator

TABLE 10. AVERAGE VELOCITY DETERMINED FROM WIDTHWISE VELOCITY SURVEYS, BASED ON FIGURE 40

No. of Points in Survev

Sample Station	1		2		4	
	Avg. Vel. (m/sec)	% Diff.	Avg. Vel. (m/sec)	% Diff.	Avg. Vel. (m/sec)	% Diff.
1	.82	+28.1	.61	-4.7	.63	-2.3
2	.97	+73.2	.39	-29.5	.55	-2.2
3	.42	-4.5	.37	-17.0	.48	+8.0
4	.93	+14.8	.85	+4.9	.79	-2.2
5	.43	-23.2	.45	-20.5	.67	+19.2

Sample Station	5		6
	Avg. Vel. (m/sec)	% Diff.	Avg. Vel. (m/sec)
1	.61	-5.0	.64
2	.53	-5.4	.56
3	.45	+2.7	.44
4	.80	-1.7	.81
5	.61	+8.2	.56

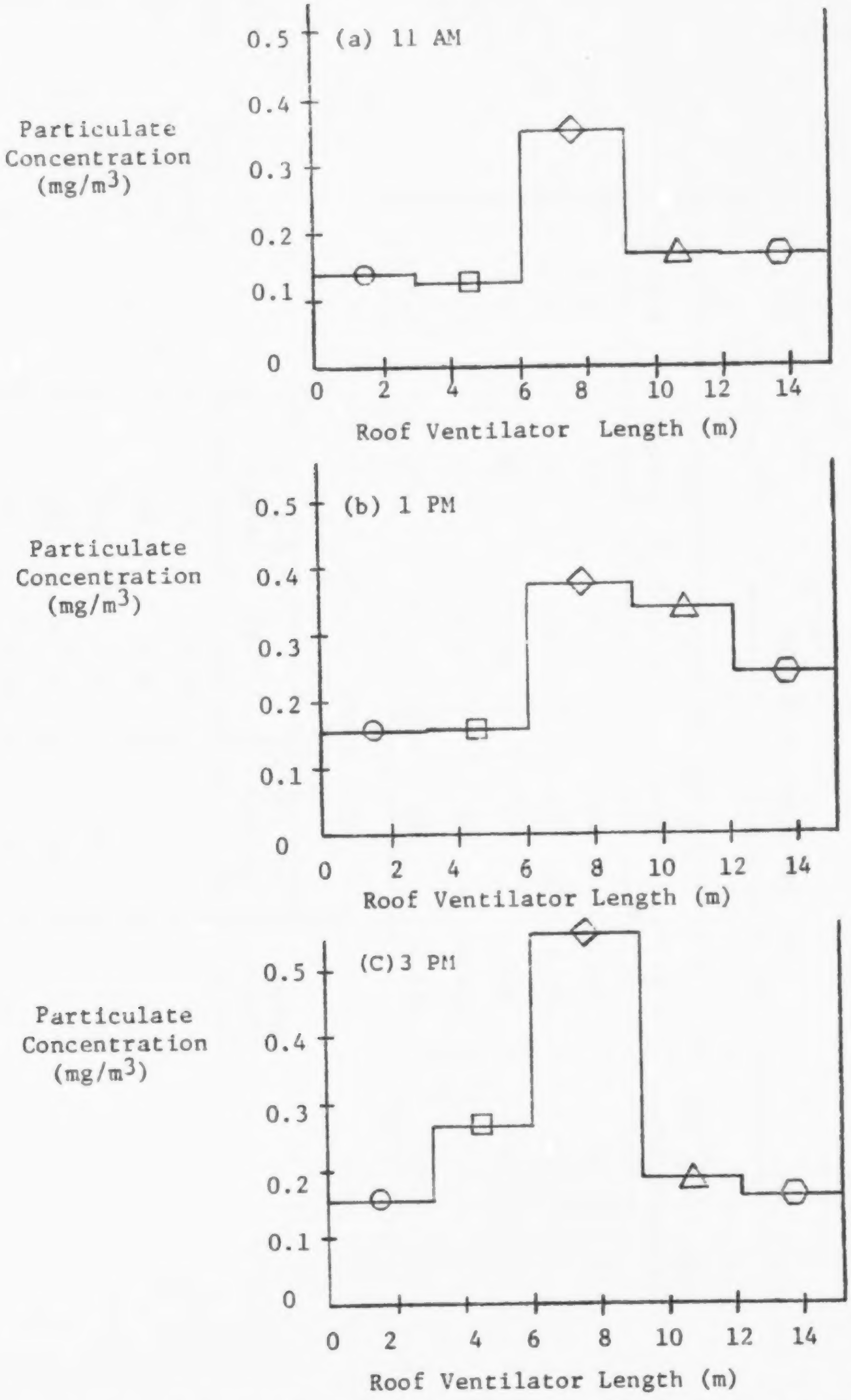


Figure 41. Particulate concentration profiles for roof ventilator emission example problem

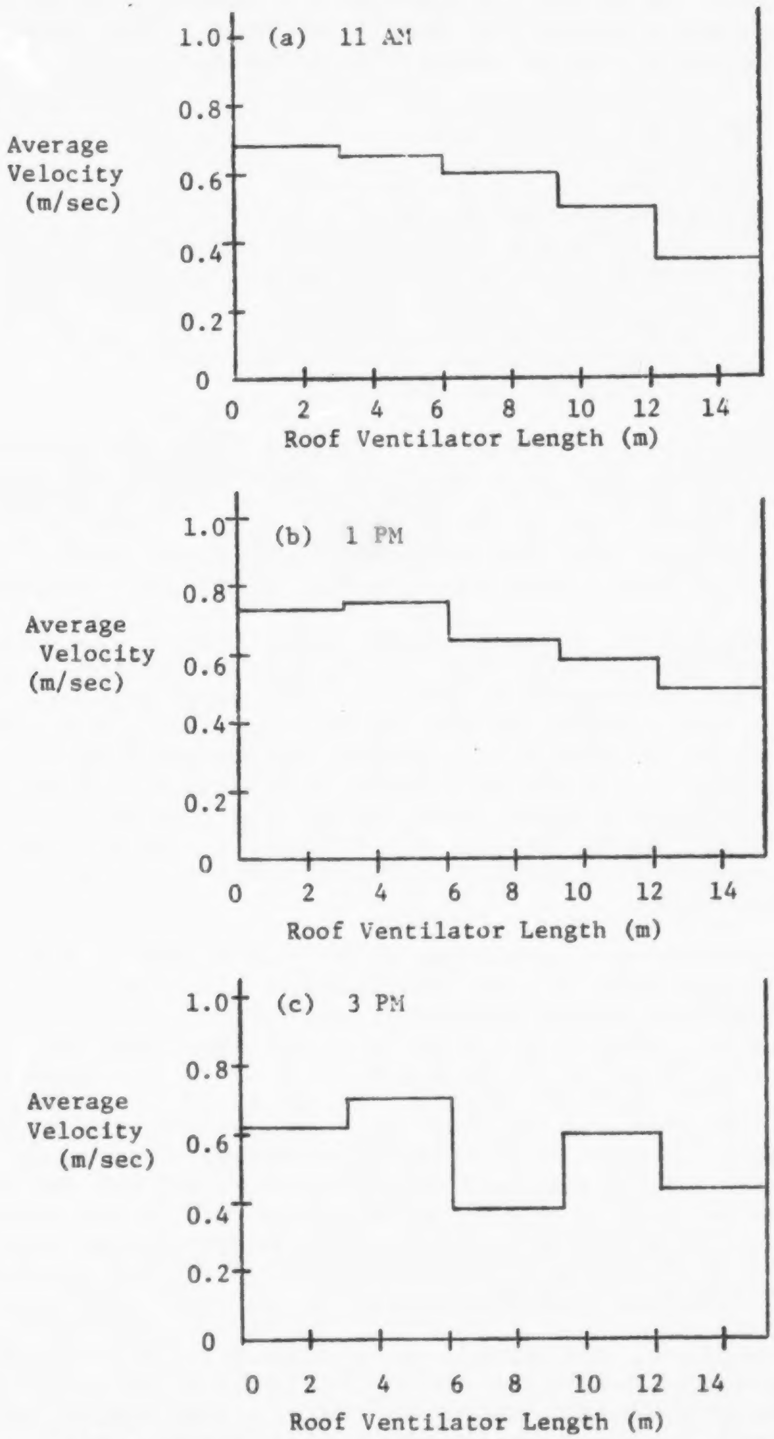


Figure 42. Average velocity profiles for roof ventilator emission example problem

The total emission during the six hour period was calculated following a number of simple methods. The basic emission calculation procedure followed the formula:

$$E = \sum_{i=1}^{N} \sum_{j=1}^{M} (C_j \overline{V}_j A_j) t_i$$

Where:
E = total emission (gm)
C = particulate concentration (gm/m^3)
N = number of time increments
M = number of sample stations
$\overline{V}$ = average velocity (m/sec)
A = cross sectional area (m^2)
t = time interval (sec)

The first calculation was made assuming that the profiles shown in Figs. 41 a,b,c and 42 a,b,c each represented the average conditions for a two-hour period (41a and 42a represent the period from 10:00 a.m. to 12:00 p.m., etc.). Several emission calculations using various combinations of the data from Figs. 41 and 42 were then compared with the first calculation.

The results of these example calculations are shown in Table 11. It can be seen that consideration of the actual variation of concentration and velocity with time and location is not important, since averaging all concentration and velocity data from Figs. 41 and 42 to single values resulted in only a 3.1% difference from the multistep calculation. This result tends to support the applicability of the concept of a manifold system, such as specified in EPA method 14, which theoretically results in average concentration measurements from a number of sampling locations.

Considering only averaged data from 3 sample stations, the center and both ends of the ventilator, also had little effect on the calculated total emission, resulting in a 5.8% difference. However, when only data from a single port was used to calculate the emission from the entire 15.24 m length of roof ventilator, the "error" ranged as high as 74.4%. This result indicates the need for no less than three velocity measurement stations in the roof ventilator system covered by the present velocity measurement specification of EPA Method 14, which requires only a single measurement point for every 85 m of length. The flow through aluminum potroom roof ventilators may be more uniform than that encountered at the Hitchcock Industries field test site, however.

To summarize, the sampling technique demonstrated through the test program described above consists of velocity and particulate concentrations at an unspecified number of sampling stations near the base of the roof ventilator, using widthwise

TABLE 11. CALCULATED EMISSIONS FOR EXAMPLE PROBLEM

Total Emission, $E = \sum_{i=1}^{N} \sum_{j=1}^{M} (C_j \overline{V}_j A_j) t_i$

N = Number of Time Increments
M = Number of Sample Locations

N	M	C_j (gm/m^3)	$\overline{V}_j$ (m/sec)	A_j (m^2)	t_i (sec)	E (gm)	% Difference
3	5	Individual values From Fig. 41 a,b,c	Individual values From Fig.42a,b,c	5.58	7200	79.8	-
3	1	Average values From Fig.41a,b,c	Average values From Fig.42a,b,c	27.9	7200	82.7	+3.6
1	1	Average value From Fig. 41	Average value From Fig. 42	27.9	21,600	82.3	+3.1
3	3	Individual values From Fig.41a,b,c at Stations 1,3,5	Individual values From Fig.42a,b,c, at Stations 1,3,5	9.3	7200	81.3	+1.9
1	1	Average value From Fig. 41 at Stations 1,3,5	Average value From Fig. 42 at Stations 1,3,5	27.9	21,600	84.4	+5.8
3	1	Individual values From Fig. 41 at Station 3	Individual values From Fig 42 at Station 3	27.9	7200	133.4	+67.2
1	1	Average value From Fig. 41 at Station 3	Average value From Fig. 42 at Station 3	27.9	21,600	139.2	+74.4
1	1	Average value from Fig. 41 at Station 5	Average value from Fig. 42 at Station 5	27.9	21,600	49.2	-38.3

velocity surveys with heated thermopile anemometers to determine average velocities and constant flow rate sampling with high volume samplers to determine particulate concentrations. An as yet unanswered question is the required number of simultaneous sampling locations over the large emission surface of a given roof ventilator. Engineering judgment will be required with regard to the expected degree of variation of effluent stream characteristics with position along the length of the roof ventilator and various economic factors involved in conducting the tests.

APPLICABILITY TO OTHER EMISSION SOURCES

The sampling technique developed for this example of a low velocity, extended dimension emission source can be generalized to other low velocity, extended dimension sources in terms of three basic choices:

1. Selection of suitable velocity instrumentation such as that listed in Table A1 having sufficient accuracy in the expected velocity range, yet sufficient durability to withstand field test conditions.
2. Selection of a high volume particulate sampler to ensure sufficient volume of gas sampled to obtain useful results.
3. Selection of appropriate sampling locations where external disturbances are minimized and sufficient information can be obtained to assess the total emissions.

The general concept should be applicable to any low velocity, extended dimension emission source where satisfactory choices can be made.

In certain cases, the heated thermopile type velocity instrument may be unsuitable, such as in basic oxygen furnace (BOF) shop ventilators, where the effluent streams reportedly are characterized by temperatures above the operating limit of this instrument. Several velocity instruments are discussed in the Appendix, which can be used as a guideline for selection of suitable velocity instrumentation.

The selection of sampling locations presents the principal problem in adapting the method to other sources, since a clear representation of this aspect was not possible within the scope of the present study. Again, at this point in time, engineering judgment must play a large role in determining the number of sampling points needed.

SECTION 5

GRAIN DRYER SAMPLING TECHNIQUES

Grain dryers are characterized by partially unconfined effluent streams, typically emanating from one or more sections of louvers which direct the flow for a short path length. Grain dryer emissions may also be characterized by extended dimensions, due to the large surface area of the louvered sections, and by low velocity streams. In the present study, grain dryer sampling methodology was reviewed, and a program for evaluation of techniques and instrumentation for measurement of grain dryer emissions was undertaken.

REVIEW OF SAMPLING METHODOLOGY

As in the case of roof ventilator emissions, contacts with commercial firms indicated that standard techniques for grain dryer emission measurements are not well established. In general, though, equipment specified for grain dryer applications have followed EPA Reference Methods or ASME Power Test Codes (Ref. 36). The sampling equipment has been deployed in various ways, generally employing some sort of collection stack but often merely inserted in the effluent stream.

Meiering, et al (Refs. 37, 38) developed a particulate collection box, shown schematically in Fig. 43, which could be attached directly to the surface of a grain drying column. A large number of these devices were used over extended periods to study the emission of particulate matter from the actual drying process in order to examine methods for reduction of emissions. No measurements of particulate matter emitted from the actual grain dryer structure into the atmosphere were attempted, however.

Reference 39 reports on grain dryer particulate emissions tests performed by a state regulatory agency. The test methodology adopted in this case was to attach a rectangular duct to a portion of the exhaust louvers and use EPA Method 5 to sample the stream flowing through this sampling duct. The duct extended 3.05 m (10 ft) from the surface of the louvers, and the cross sectional area of the duct amounted to 10% of the total louvered area. Only the louvers on one side of the grain dryer were sampled, and the emission measurements were noticeably affected by external wind conditions.

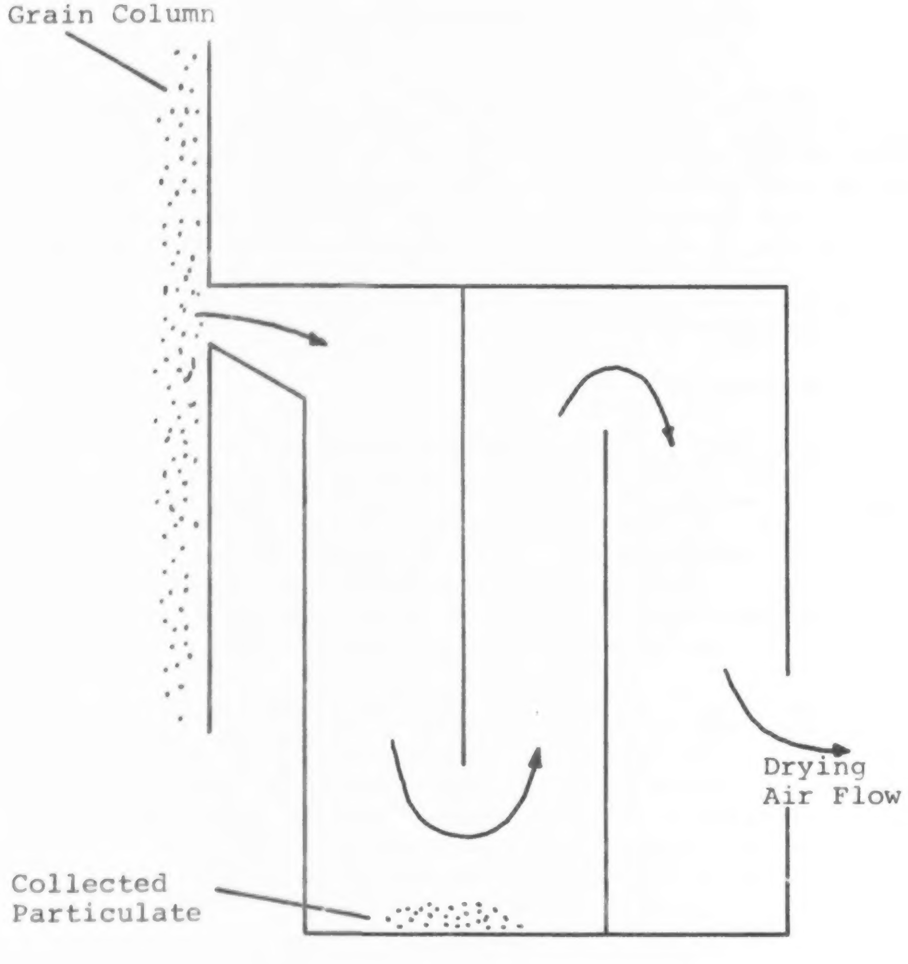

Grain Column
Drying Air Flow
Collected Particulate

Figure 43. Particulate collection device used for grain dryer emissions measurement (Refs. 37, 38)

Tests conducted by the EPA on a grain dryer with a screen filter type emission control device are reported in Ref. 40. In this instance, the exhaust louvers were removed from the emission surface before the measurements were made. Sampling points were established at the midpoints of 12 equal area segments over the 2.44 m x 7.32 m exhaust surface. A Method 5 type sampling probe was inserted in a 0.46 m (1.5 ft) "stovepipe" flow straightener and traverses of the exhaust surface were performed. Pitot tube and hot wire anemometer measurements were made, but the results were considered unreliable, and therefore manufacturers specifications rather than actual velocity measurements were used to determine the sampling rate.

Tests with a high volume sampling train are also reported in Reference 40; correlation between the high volume and Method 5 trains were generally poor in these grain dryer emission tests, however.

The variety of approaches to grain dryer emission measurement is indicative of the general lack of standard test methodology. As in the case of roof ventilator emission measurements, assessment of the accuracy of the various measurement techniques reported here was not possible. Engineering judgment as to the feasibility and accuracy of the various methods was the basic criterion for selection of these techniques.

PRELIMINARY INFORMATION

A potential field test site was located at a Minneapolis area manufacturing plant, Honeymead Products Company. This facility includes a column type grain dryer, Carter-Day model HC-66, used primarily for drying sunflower seeds used in the production of sunflower oil. Preliminary arrangements were made to conduct a field test program at the Honeymead grain dryer site. However, this field test program was not completed due to inactivity of the grain dryer, first due to a labor strike and then due to decreased demand for sunflower oil. Several detailed inspections of the grain dryer, including the exterior exhaust louvers as well as the interior flow passages, fans, burners, grain columns, screens, etc., were made, however.

In lieu of a preliminary field test program, the grain dryer manufacturer was contacted for information concerning expected flow rates, particulate concentrations, and difficulties to be encountered in grain dryer emission measurements. Information was gathered on the Honeymead grain dryer as well as several other models used in various parts of the country.

MODEL STUDIES

The laboratory model studies program was developed on the basis of the information presented above. A laboratory model representative of the emission plane of a typical grain dryer was designed and fabricated, and this model was used to evaluate techniques and instrumentation for use in measurement of particulate emissions from grain dryers.

Model Design and Fabrication

A model of the upper portion of a typical grain dryer was fabricated and attached to the existing ductwork and diffuser section constructed for the roof ventilator model studies (Figure 44). The primary intent of the model design was to simulate the interaction of the internal flow of a grain dryer with the external atmospheric conditions. A schematic diagram of the flow through the grain dryer model is shown in Figure 45. This flow passage simulates the flow through a typical Carter-Day column type grain dryer.

Two sets of exhaust louvers were included in the grain dryer model. One set of louvers is shown in Figs. 44 and 46, the other being directly opposite this set on the other long side of the grain dryer model. The total exhaust louver surface area of the grain dryer model amounted to 1.24 m^2, or about 6% of a typical column type grain dryer. The length and width dimensions of the model were scaled approximately to match the Honeymead dryer.

The same aerosol generation system used in the roof ventilator tests, illustrated in Fig. 26, was used to introduce particulate matter into the grain dryer model exhaust. This model aerosol had a mass median diameter of approximately 2 μm. Typical grain dryer particulate emissions are generally expected to include much larger particles. However, the relatively high density of the model salt particles as compared to typical grain particles resulted in an aerodynamic particle size which was a reasonable model of grain dryer particulate for the purpose of the laboratory model testing.

Flow Velocity Studies

Based on the available information on flow rates through various grain dryers, velocities in the range of 1-4 m/sec are expected in grain dryer exhaust streams. Based on the extensive evaluation of velocity instrumentation shown in the Appendix, the instrument selected as having the greatest potential for use in grain dryer sampling was the heated thermopile anemometer. The Haystings Raydist PCI-30 anemometer, the same instrument selected for roof ventilator testing, was chosen for evaluation on the basis of an overall judgment of accuracy in

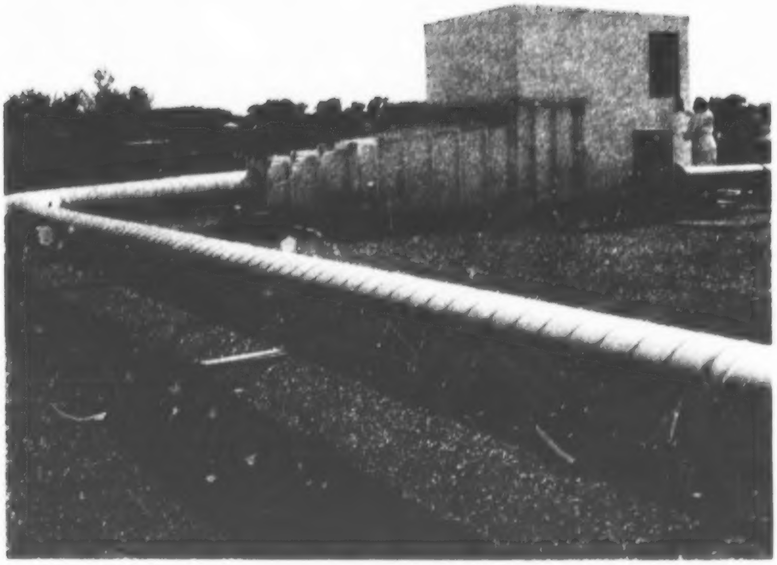


Figure 44. Grain dryer model constructed with existing air supply at Medicine Lake Laboratory

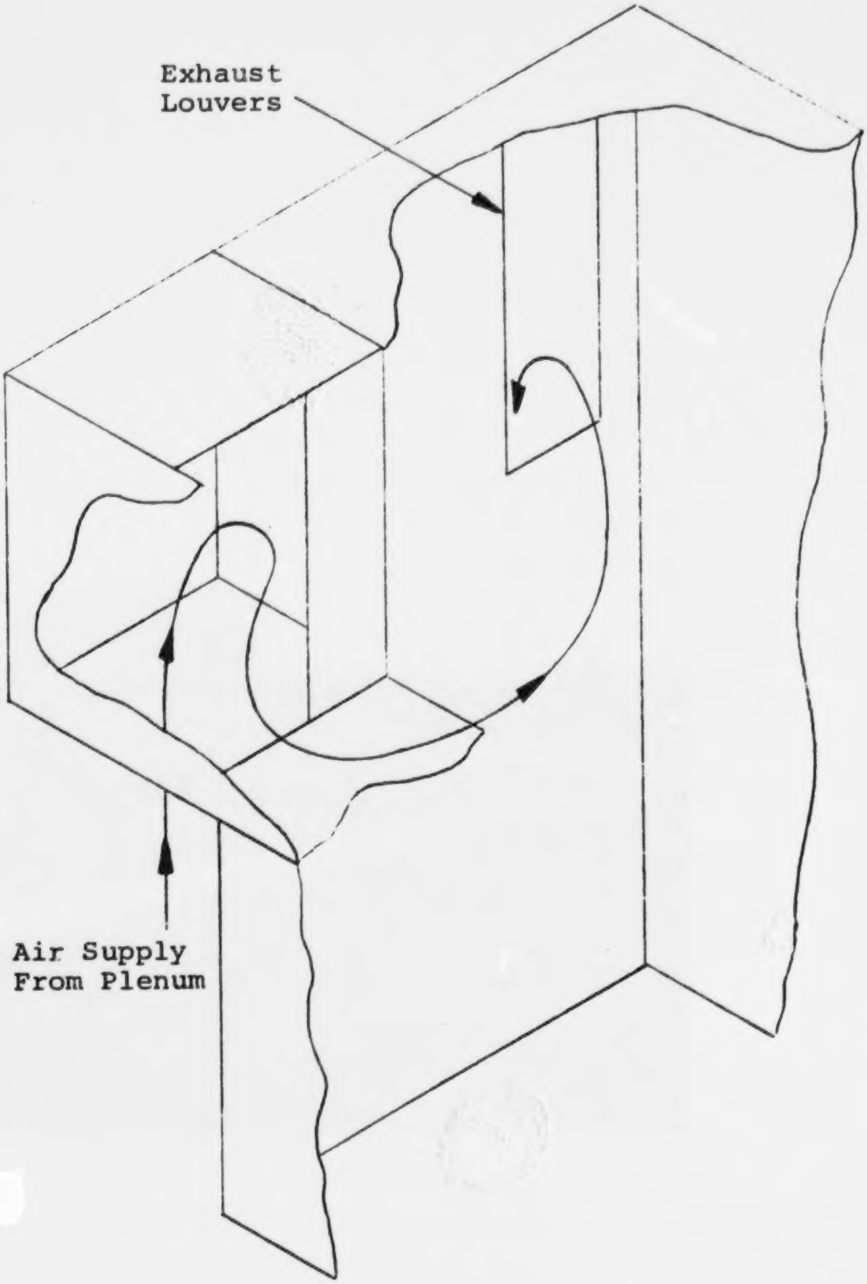

Exhaust
Louvers
Air Supply
From Plenum

Figure 45. Cutaway of grain dryer model showing air flow passage on one side of model

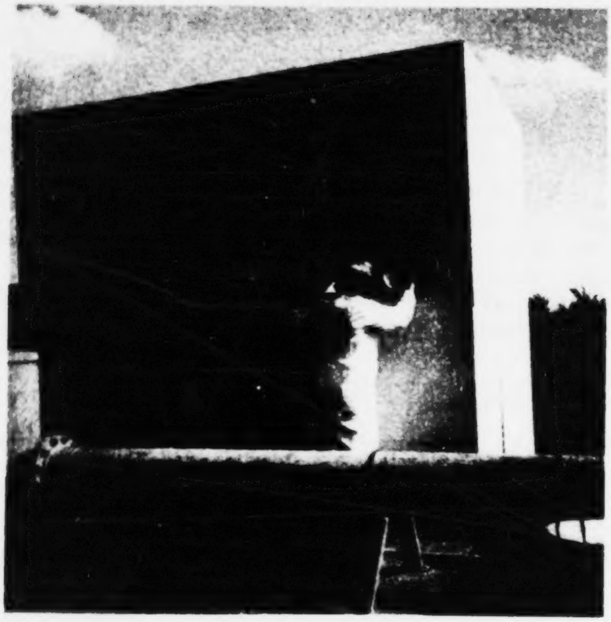


Figure 46. Grain dryer model with exhaust louvers

the expected velocity range, ease of handling, and ruggedness.

The basic technique chosen for volumetric flow measurement was to place the anemometer directly at the outlet of the exhaust louvers as shown in Fig. 47. This technique was chosen in order to minimize potential interference with the exhaust flow field which might be introduced by a collection duct or hood and to eliminate any modifications of the dryer itself, which might be required, such as removal of the louvers as reported in Ref. 40. The sensing head of the anemometer was aligned with the angle of the louvers, in this case 45°.

A number of velocity traverses were made with the heated thermopile anemometer, employing two matrices of sampling points as illustrated in Fig. 48. Atmospheric winds were also measured during these tests and were found to vary from a minimum of 0.15 m/sec to a maximum of 5.1 m/sec. The average wind velocity was roughly 1.5 m/sec. The wind direction varied from parallel to the exhaust through the louvers to perpendicular to the exhaust. In order to simulate the result of an obstruction to the exhuast flow path, such as proximity to a building, or an internal blockage within a grain dryer, approximately 45% of the louver area was blocked off during several of the velocity measurements.

Results of these tests are presented in Fig. 49, which compares the volumetric flow rate determined from the velocity traverses of the two exhaust louver faces with the actual flow rate measured in the supply ductwork upstream of the grain dryer model. As can be seen from this Figure, all data lies within an accuracy range of ±15% regardless of the wind velocity, wind direction, or degree of blockage of the exhaust louvers. These results indicate the usefulness of the basic measurement technique of simply deploying the anemometer at the outlet of the louvers.

Particulate Concentration Studies

The sampling instrument chosen for particulate measurement studies was the high volume sampler and probe developed for use in roof ventilator particulate emission measurements. This probe was deployed at the surface of the exhaust louvers (Fig. 50) for the same reasons as the velocity instrument, i.e., in order to minimize flow disturbance and required modifications.

A number of concentration measurements were made by traversing the surface of the exhaust louvers. Two sampling matrices were employed, as shown in Fig. 51. Wind conditions were comparable to those encountered during the velocity testing. A constant sampling rate was used at all of the sampling points on each of the two sets of exhaust louvers. The selected rate was based on isokinetic sampling at the

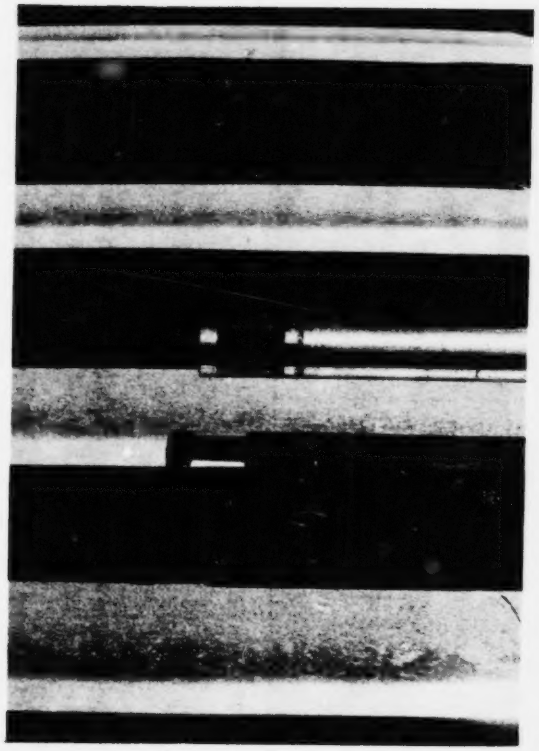


Figure 47. Heated thermopile anemometer deployed at surface of exhaust louvers

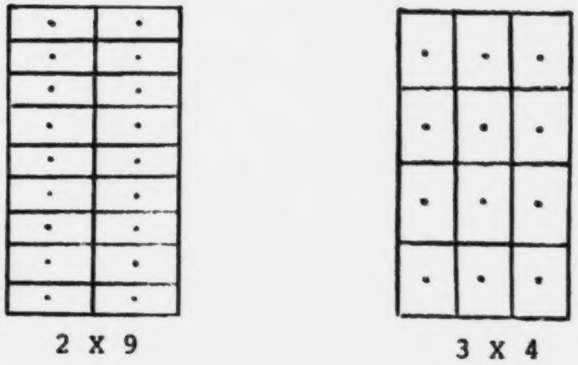


Figure 48. Sampling point matrices used for velocity traverses of grain dryer model

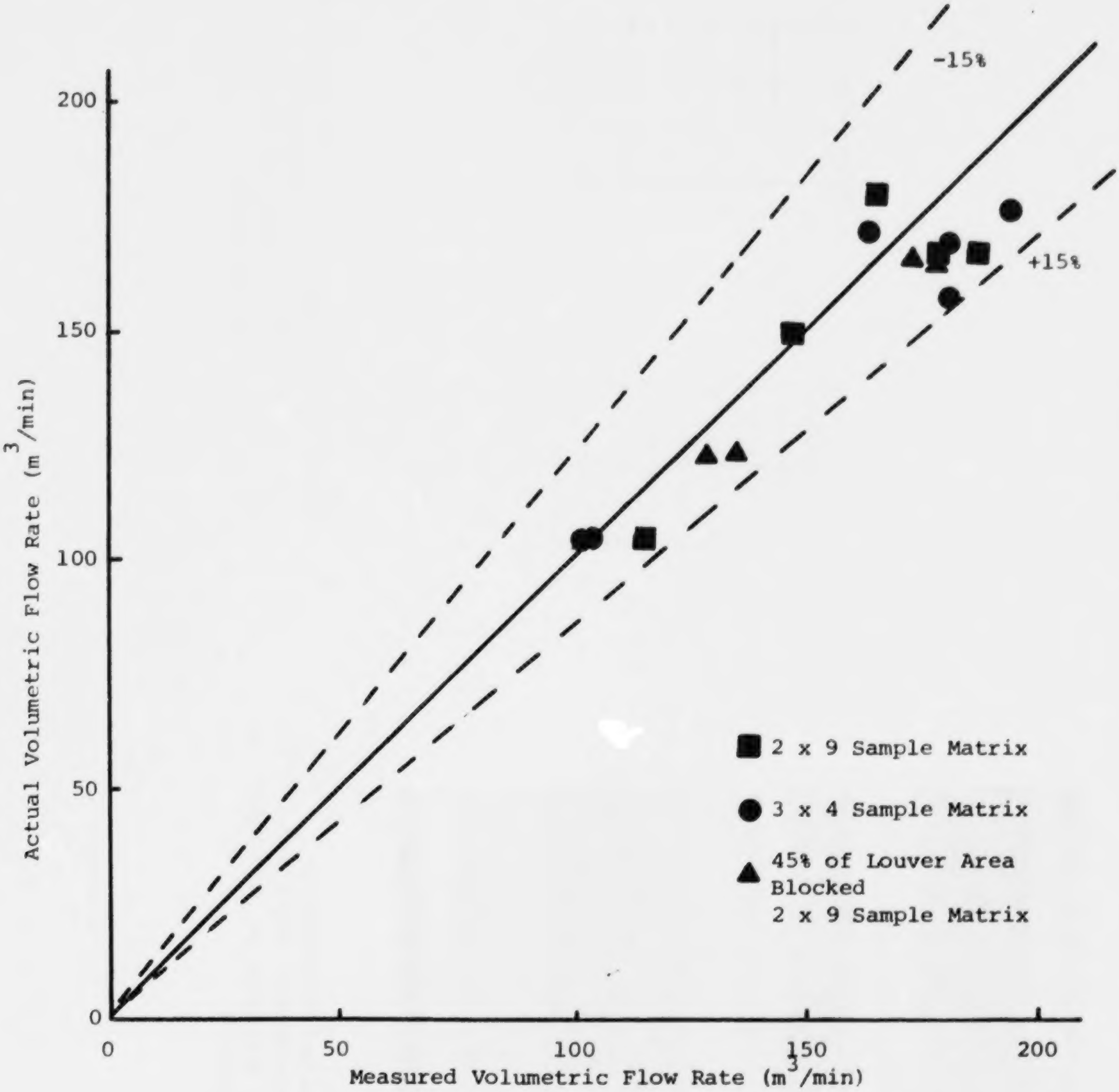


Figure 4 9. Volumetric flow rate determined with heated thermopile anemometer at exhaust louvers of grain dryer model

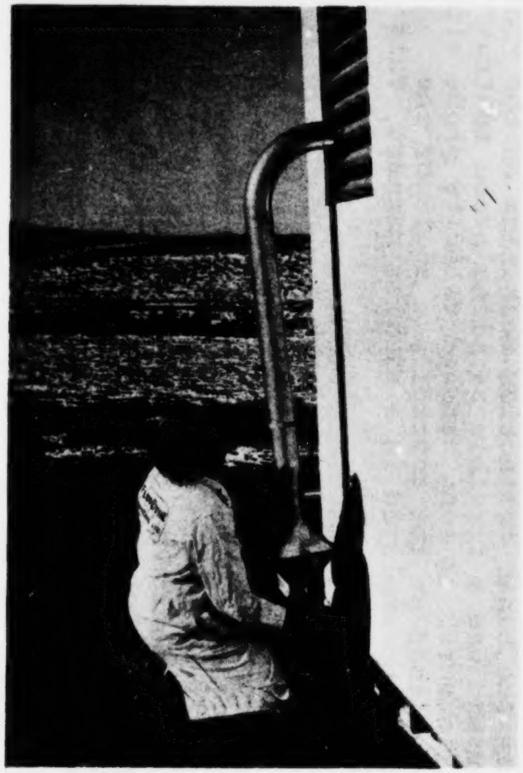


Figure 50. High volume sampler deployed at surface of exhaust louvers for particulate traverses

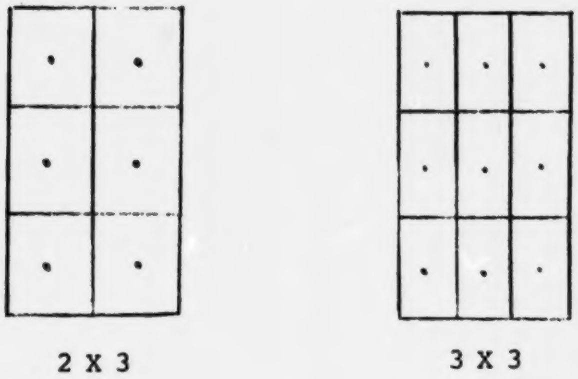


Figure 51. Sampling point matrices used for particulate traverses of grain dryer model

average velocity determined from velocity surveys with the heated thermopile anemometer, rather than attempting to attain isokinetic sampling at each individual point.

The results of the particulate concentration measurements are shown in Fig. 52. The actual concentration was determined from concentration traverses in the ducting upstream of the grain dryer model. The results indicate that the measured concentration was generally within ± 25% of the actual. Measurements made with a 3 x 3 sampling matrix, or a "balanced" matrix as proposed for rectangular ducts in Ref. 2, appeared to be more reliable than those made with a 2 x 3 matrix. Again, the results indicate that simply deploying the sampling probe at the surface of the exhaust louvers provides reasonable results.

EVALUATION OF SAMPLING TECHNIQUE

The basic sampling technique developed for grain dryer emission measurements involves the use of a heated thermopile anemometer for velocity measurements and a high volume particulate probe for particulate concentration measurements, both of these instruments to be traversed across the surface of the exhaust louvers. Based on the limited data presented here, a balanced matrix scheme of sampling points is recommended. The total number of sampling points should be chosen such that the total time required for traversing the louver surface is compatible with a period of relatively steady operation of the grain dryer.

The principal problem in employing this method on full scale grain dryers is gaining access to the exhaust louvers, which are usually situated a great distance above the ground. Therefore, some support scaffolding will generally be required. An alternative to the use of support scaffolding, however, might be to situate the basic collection mechanism on the roof of the grain dryer and use a flexible sampling probe to traverse the exhaust louvers. A long handled velocity probe with the sensing head inclined at the appropriate angle of the exhaust louvers could be employed in a similar manner. This concept is illustrated in Fig. 53.

APPLICABILITY TO OTHER EMISSION SOURCES

The sampling technique developed for this example of a partially unconfined particulate emission source should be applicable to other partially unconfined sources for which a suitable choice of a measurement plane can be made. In the case of grain dryer emissions, the louvers confine the flow for a sufficient length so as to provide a flow field which is relatively unaffected by the external conditions near the exhaust surface. In the case of roof ventilators, in contrast,

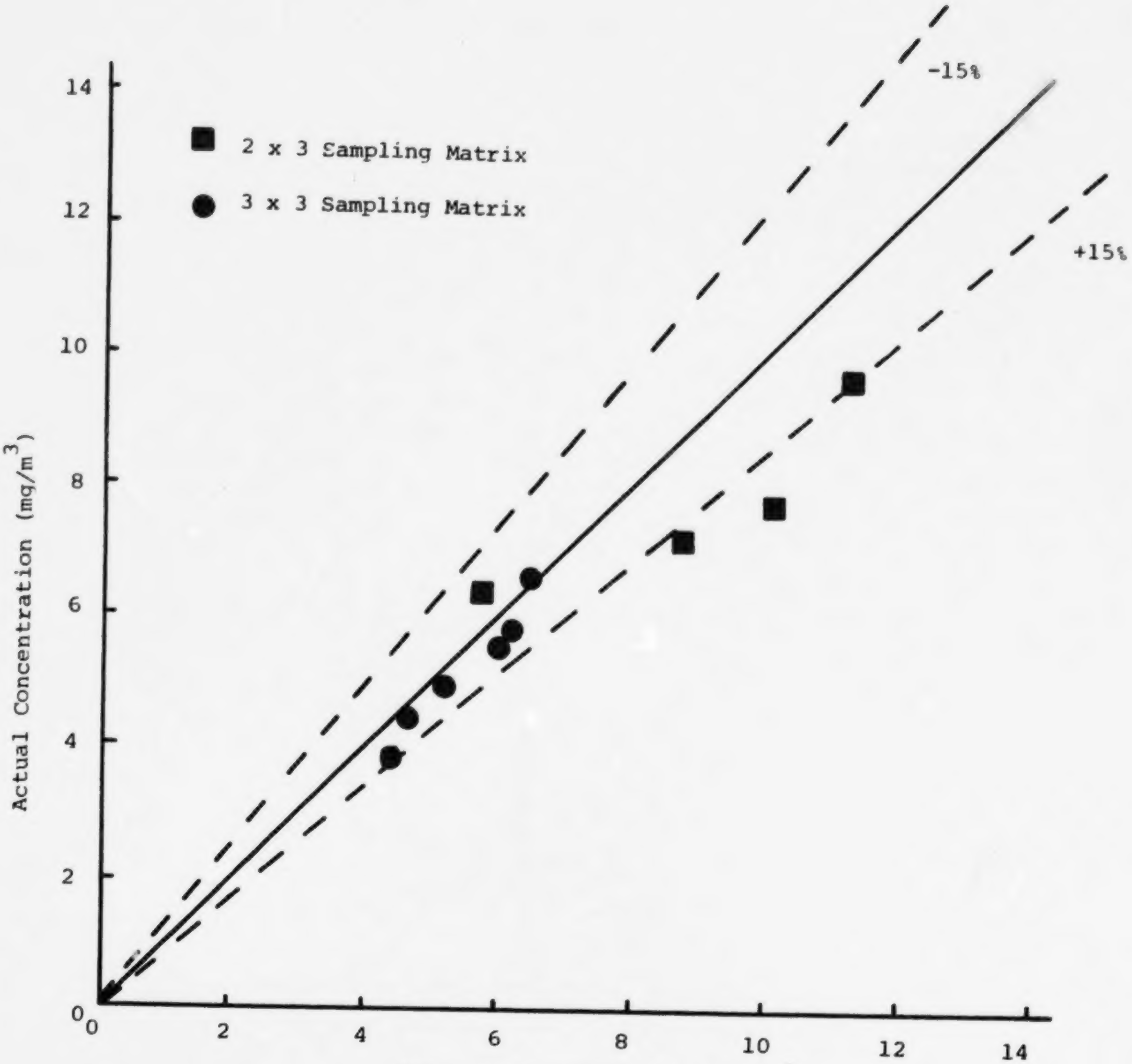


Figure 52. Particulate concentration measured with high volume sampler at exhaust louvers of grain dryer model

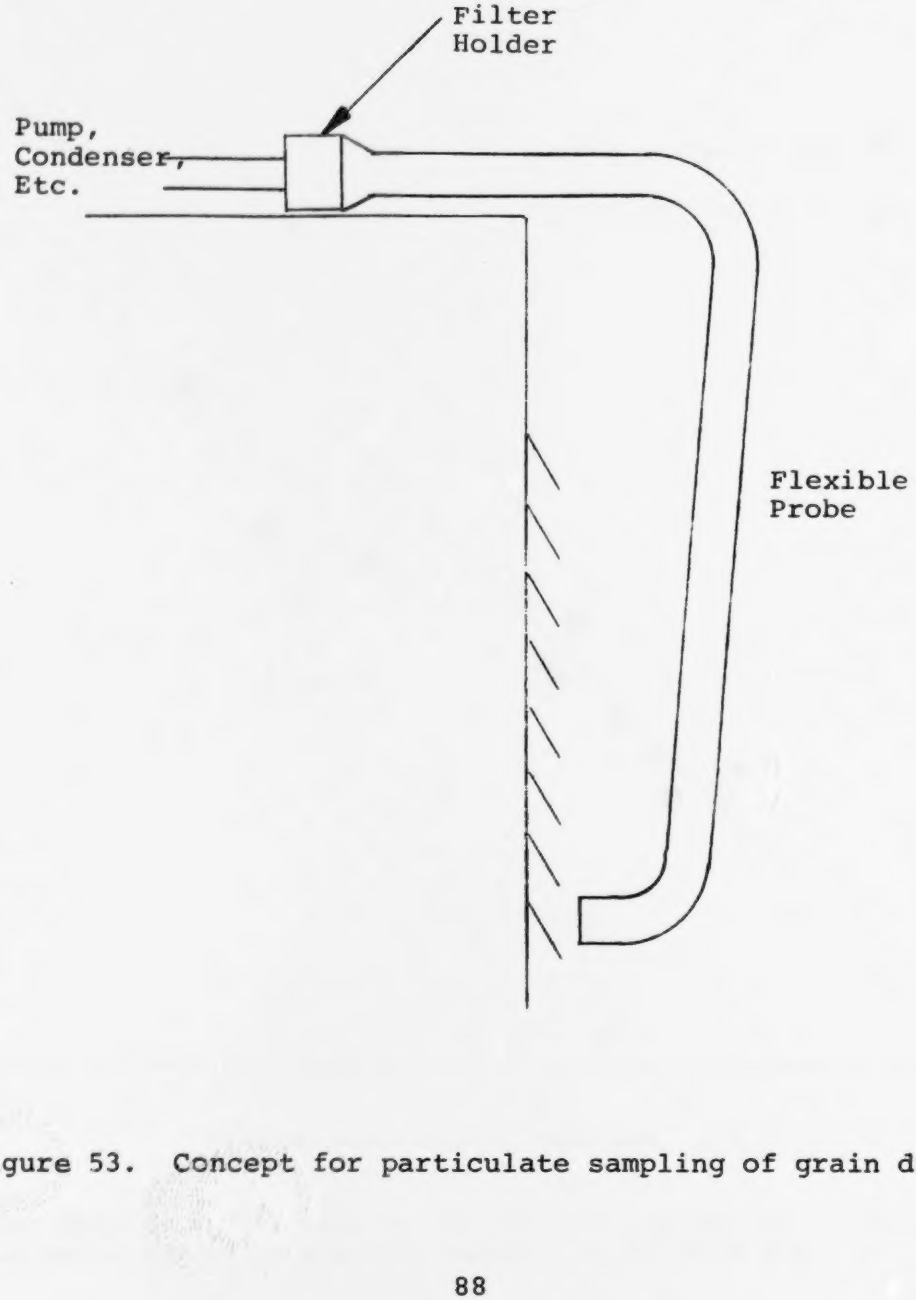

Filter Holder
Pump, Condenser, Etc.
Flexible Probe

Figure 53. Concept for particulate sampling of grain dryers

the low velocity, circulatory flow field emanating from the exhaust surface was shown to be unsuitable for emission measurements due to the severe interaction with external conditions.

It is evident, therefore, that emission measurements can be made externally only if the partial confinement results in a suitable flow field. For partially unconfined emission sources which can not readily be classified in this matter by engineering judgment, some simple flow visualizaiton studies may provide the means to decide if measurements can be made externally, as with grain dryers, or if an internal site must be identified, as with roof ventilators.

This method is very likely not applicable for totally unconfined emission sources. Particulate emissions from this type of emission source should probably be measured with a sampler such as the "exposure profiler" developed by Cowherd, et al (Refs. 15, 41) or the fugitive emissions sampler reported by Jorgenson, et al (Ref. 42).

SECTION 6

WET SCRUBBER SAMPLING TECHNIQUES

The principal characteristic of the flow downstream of a scrubber is the presence of saturated gas and/or entrained liquid droplets. It was determined that various problems associated with this characteristic, and with the various devices used to remove liquid droplets from the flow (mist eliminators), generally cause the standard Method 5 sampling train to be inadequate for emission measurements. In order to examine possible alternative sampling techniques, a program of methodology review, field testing and model testing, following the same basic approach taken for the study of roof ventilator and grain dryer sampling techniques, was undertaken.

REVIEW OF SAMPLING METHODOLOGY

A wide variety of sampling equipment has found application in sampling scrubber exhaust streams, including such devices as wet and dry impingers, impactors with various substrates, cyclone precutters, and fabric filters. This is due in part to the wide variety of pollutants, both gaseous and particulate, which are found in scrubber applications. A partial list of particulate sampling trains used by various organizations may be found in Ref. 43.

Several aspects which must be considered in scrubber emission measurements are specified in Refs. 44 and 45. When sampling a wet scrubber system, particulate concentration should be analyzed on a dry gas basis. Thus, the dry gas flow rate and the volume of entrained liquid must be measured. In addition, isokinetic sampling is very important since droplet sizes may have a wide range depending on the particular entrainment separator used.

Scrubber sampling methods have usually specified that the sample probe be heated (Refs. 16,22,43). The required temperatures may be critical depending on both the chemical makeup of the exhaust gas and the sampling train. Temperatures should generally remain above the exhaust gas dewpoint, but not so high as to vaporize various liquid pollutants of interest. As in the case of roof ventilator and grain dryers sampling, engineering judgment plays a large role in the selection of sampling equipment and techniques (Refs. 17, 44).

A great deal of information concerning sampling techniques and problems was obtained through contacts with twelve manufacturers of wet scrubber systems. Since scrubber manufacturers often tend to specialize in wet scrubber systems for a particular industry, the reported sampling techniques varied according to the type of pollutants encountered in these various industries. The most common practice was found to be the use of the basic Method 5 sampling train with modifications required to overcome specific problems encountered. Typical modifications included various placements of the filtration assembly relative to the other sampling train components and the use of liquid droplet precutters at the sampling probe inlets. Precutters are usually of the cyclone type, several of which are described in Ref. 45, or inertial impaction separators. One type of precutter is illustrated in Fig. 54. Occasionally, totally different sampling techniques have been employed in particularly troublesome situations.

Other difficulties discussed in these manufacturer contacts included the variation of particulate concentrations in scrubber system ductwork due to gravitational settling and wall impingement and problems associated with sustained high temperature of heated sampling probes. In certain cases, the probe temperature of 121°C (250°F) specified by Method 5 was suspected to cause breakdown of various particulates. Several manufacturers also have encountered unusually large degrees of droplet carryover from the mist eliminators in certain systems, usually in small scrubber systems or systems with high velocities. One manufacturer observed that liquid entrainment became very severe above a critical velocity on the order of 11.7 to 12.7 m/sec (2300 to 2500 ft/min).

Possibly the most common difficulty reported was the presence of cyclonic flow in the stream to be sampled, often induced by the mist eliminator. This problem was observed by many manufacturers. In addition, seven of nine scrubber systems discussed in Ref. 21 had swirling or cyclonic flow. Sampling problems reported in Ref. 21 were handled either by orienting the sample probe in the direction of maximum velocity or by adding permanent "egg crate" or vane-type flow straighteners. The use of flow straighteners ranging from bundles of stove pipes to sophisticated vane arrangements were reported by various manufacturers. Concern was expressed, however, that overall flow rate and particulate concentration may be altered when such flow straightening devices were introduced.

Cyclonic flow presents problems in determination of the volumetric flow rate since the axial component of velocity must be known at all points in a given cross section in order to calculate the volumetric flow rate through that section. A hypothetical cyclonic flow is illustrated in Fig. 55 showing the normal method for finding this axial component, which

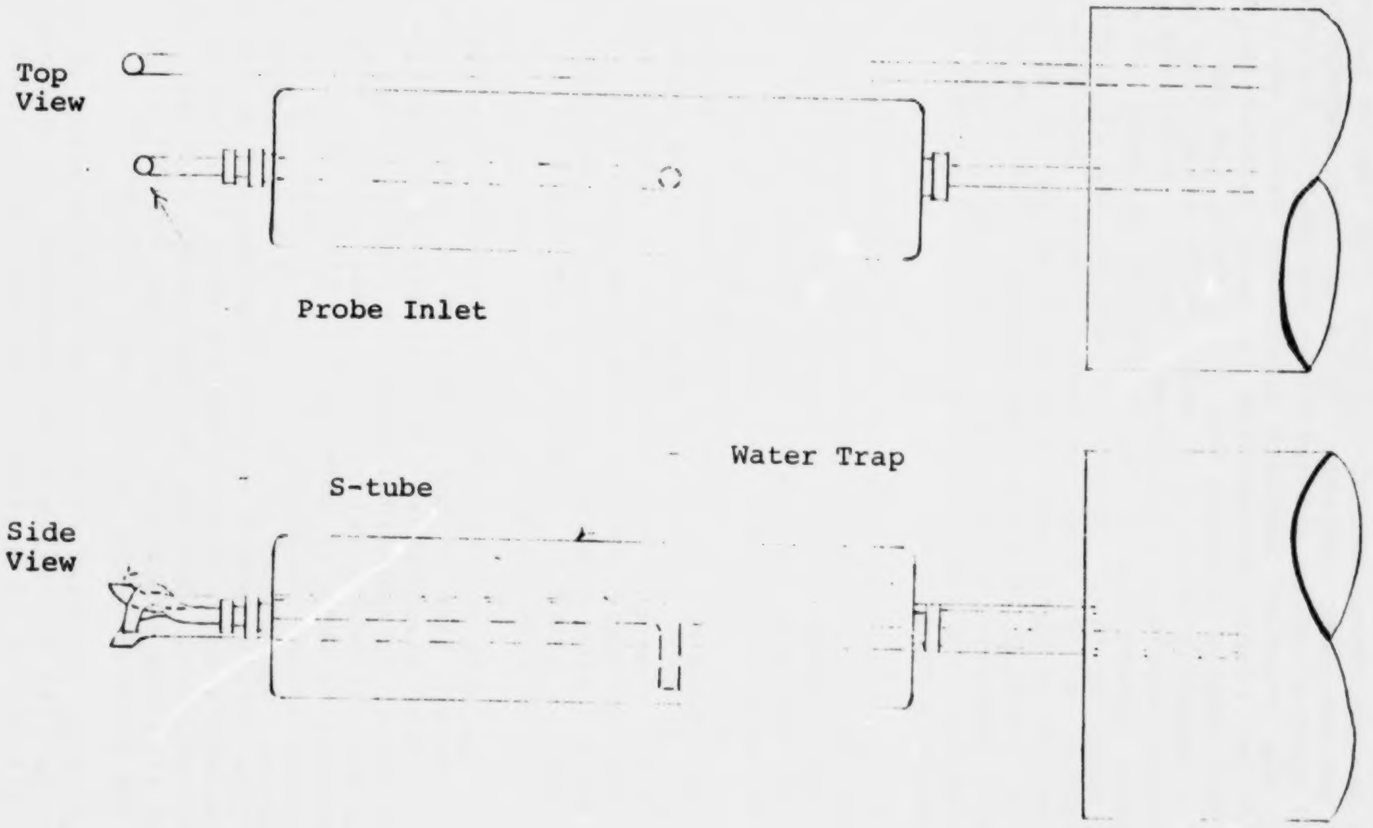
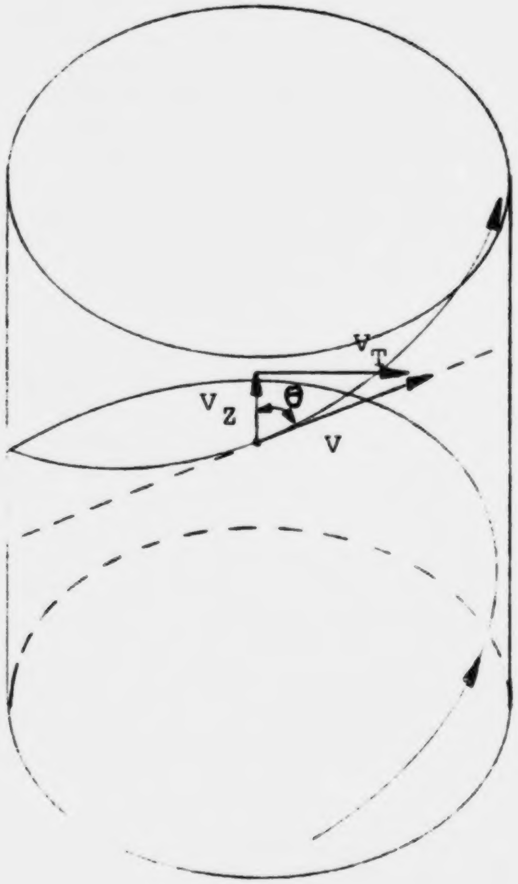

Top View
Probe Inlet
Water Trap
S-tube
Side View

Figure 54. Inertial impaction liquid droplet separator used by a wet scrubber manufacturer's test group



- - - S-tube oriented along this line

V = Actual Duct Velocity

V_Z = Axial Velocity Component

V_T = Tangential Velocity Component

θ = Angle between Axial Direction and the Flow Direction at the Sample Point

$V_Z = V \cos \theta$

Figure 55. Method used to determine axial component in a single vortex cyclonic flow

requires the ability to measure the yaw angle. If an S-type pitot tube were aligned in the axial direction and used to attempt direct measurement of the axial velocity component, the measurement would be in error since the output of a pitot tube does not correspond to the cosine of the yaw angle, as indicated by the data shown in Fig. 56 (extracted from Refs. 2 and 46).

Several studies have been made concerning sampling within vortices or cyclonic flow regions (e.g., Refs. 47-50). It has been observed that in a flow pattern consisting of a vortex motion superimposed on an axial motion, i.e. a single vortex cyclonic flow, the axial velocity profile varies considerably as the swirling velocity increases. The axial velocity component at the duct center decreases relative to the axial velocity component at larger radius values as the swirling velocity increases. Another measurement consideration is the possible effect of the inserted probe size on a cyclonic flow (Ref. 47). Insertion of a large probe in a small duct can readily disturb a cyclonic flow.

Various types of instruments have been used to determine volumetric flow in cyclonic flow fields. Several directionally sensitive pitot tubes are shown in Fig. 57. One of the most widely used is commonly referred to as the Fecheimer probe. The principle of operation of the Fecheimer probe is related to the pressure distribution around a cylinder in cross flow, as shown in Fig. 58. The static pressure angle is quite uniform at 39.25° for values of the Reynolds number in the range 10,000 - 200,000. By arranging static pressure taps at the two locations and a total pressure tap as indicated in Fig. 59 (from Ref. 52), the yaw angle can be found by rotating the probe until a null point is reached between the two static pressure taps, and the dynamic pressure is then the difference between the total and static pressure taps. Variations of this concept are illustrated in Figs. 60 and 61, extracted from Refs. 53 and 54.

Other directional sensing velocity instruments appearing in the literature include spherical head direction pitot tubes (similar to Fig. 57), and single or multiple element hot wire or hot thermopile anemometers. These devices have not been used as extensively in large duct cyclonic flow as the Fecheimer probe or its variations.

As in the case of other atypical particulate emission sources, a review of sampling methodology revealed the lack of an accepted standard sampling technique for emissions from wet scrubbers. The primary problems cited in relation to wet scrubber sampling were related to:

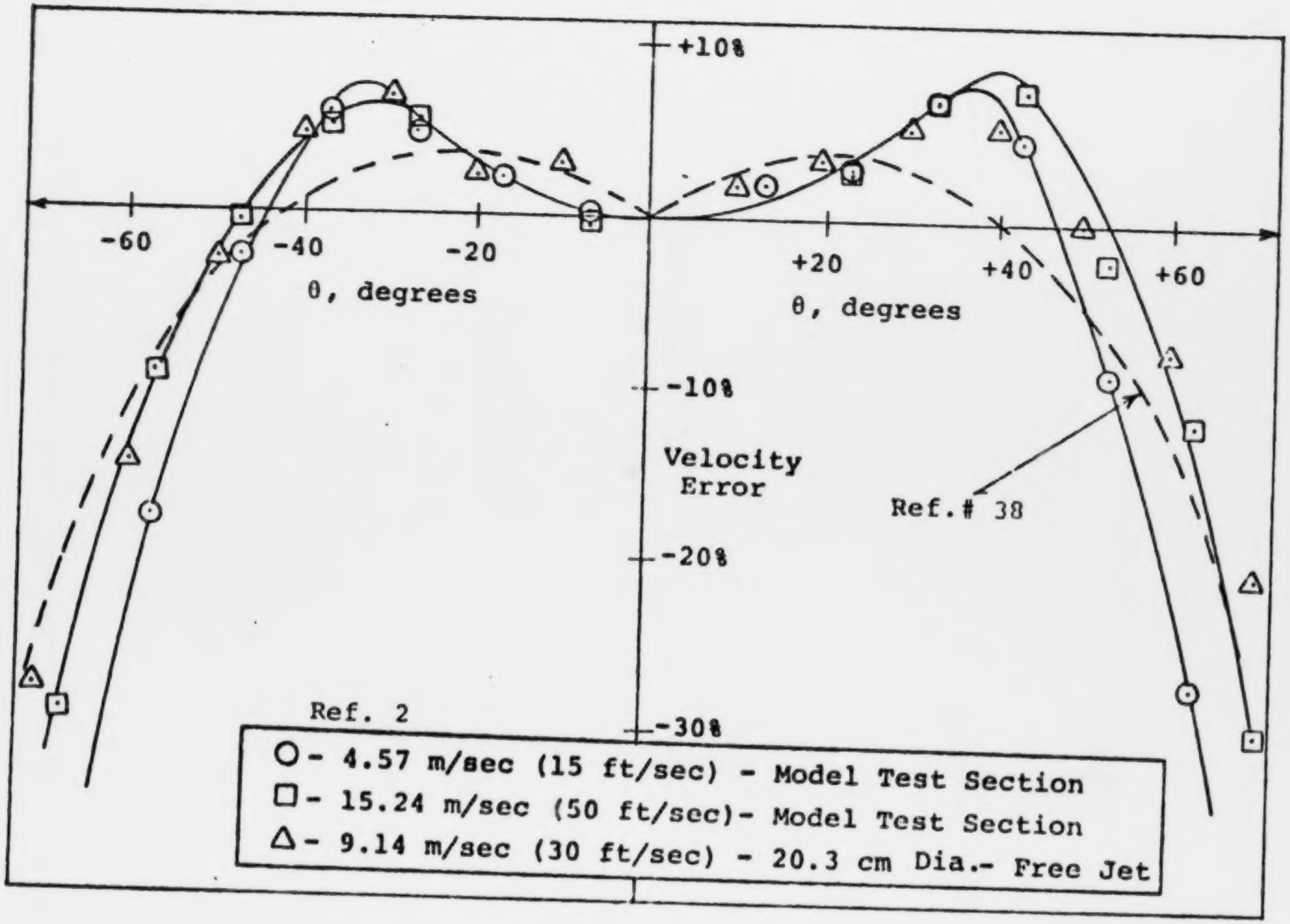


Figure 56. Velocity error with yaw angle (3/8" S-Tube)

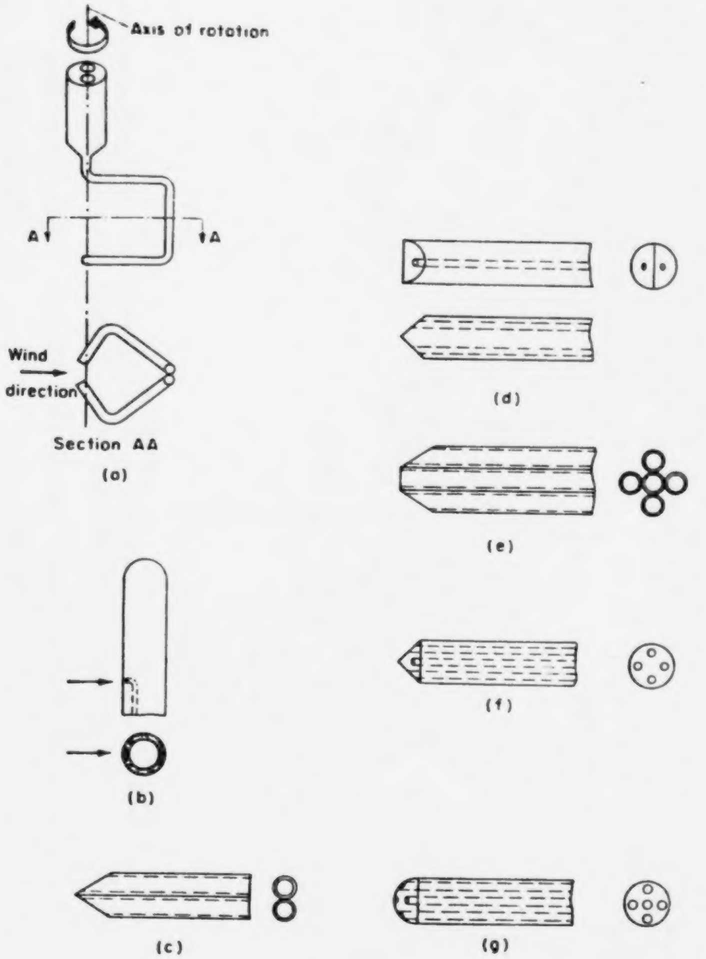

Axis of rotation
A
A
Wind direction
Section AA
(a)
(b)
(c)
(d)
(e)
(f)
(g)

Figure 57. Several types of directional pitot tubes (Ref. 51)

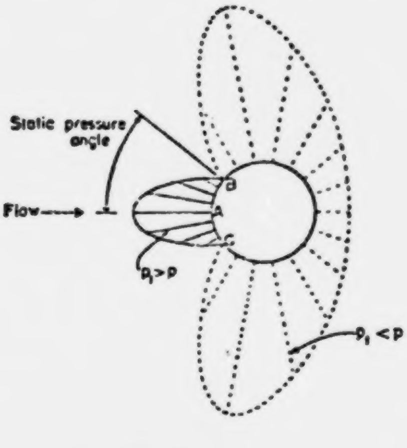

Static pressure angle
Flow
B
A
C
$p_t > p$
$p_t < p$

Figure 58. Pressure distribution over a cylinder in cross flow

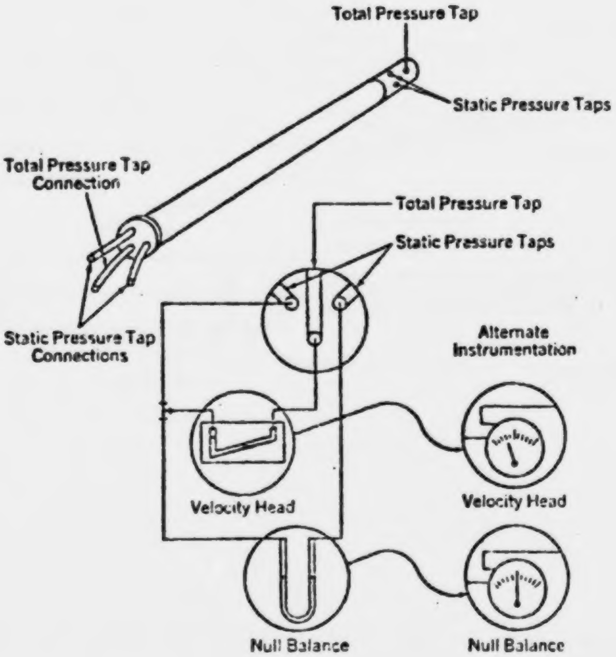

Total Pressure Tap
Static Pressure Taps
Total Pressure Tap Connection
Total Pressure Tap
Static Pressure Taps
Static Pressure Tap Connections
Alternate Instrumentation
Velocity Head
Velocity Head
Null Balance
Null Balance

Figure 59. Typical Fecheimer probe and pressure monitoring system (Ref. 52)

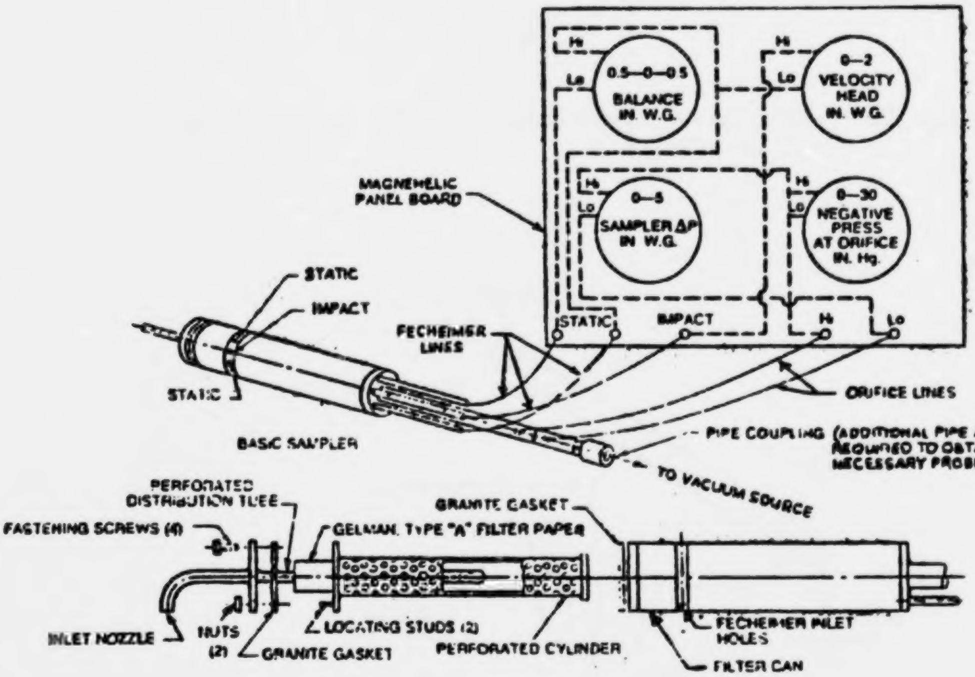

Hi
Lo
0.5—0—0.5
BALANCE
IN. W.G.
Hi
Lo
0—2
VELOCITY
HEAD
IN. W.G.
MAGNEHELIC
PANEL BOARD
Hi
Lo
0—5
SAMPLER ΔP
IN W.G.
Hi
Lo
0—30
NEGATIVE
PRESS
AT ORIFICE
IN. Hg.
STATIC
IMPACT
STATIC
IMPACT
Hi
Lo
FECHEIMER
LINES
STATIC
ORIFICE LINES
BASIC SAMPLER
PIPE COUPLING (ADDITIONAL PIPE AS REQUIRED TO OBTAIN NECESSARY PROBE Lg)
TO VACUUM SOURCE
PERFORATED
DISTRIBUTION TUBE
FASTENING SCREWS (4)
GELMAN, TYPE "A" FILTER PAPER
GRANITE GASKET
INLET NOZZLE
NUTS
(2)
GRANITE GASKET
LOCATING STUDS (2)
PERFORATED CYLINDER
FECHEIMER INLET
HOLES
FILTER CAN

Figure 60. Fecheimer Probe built into filter holder
(Ref. 53)

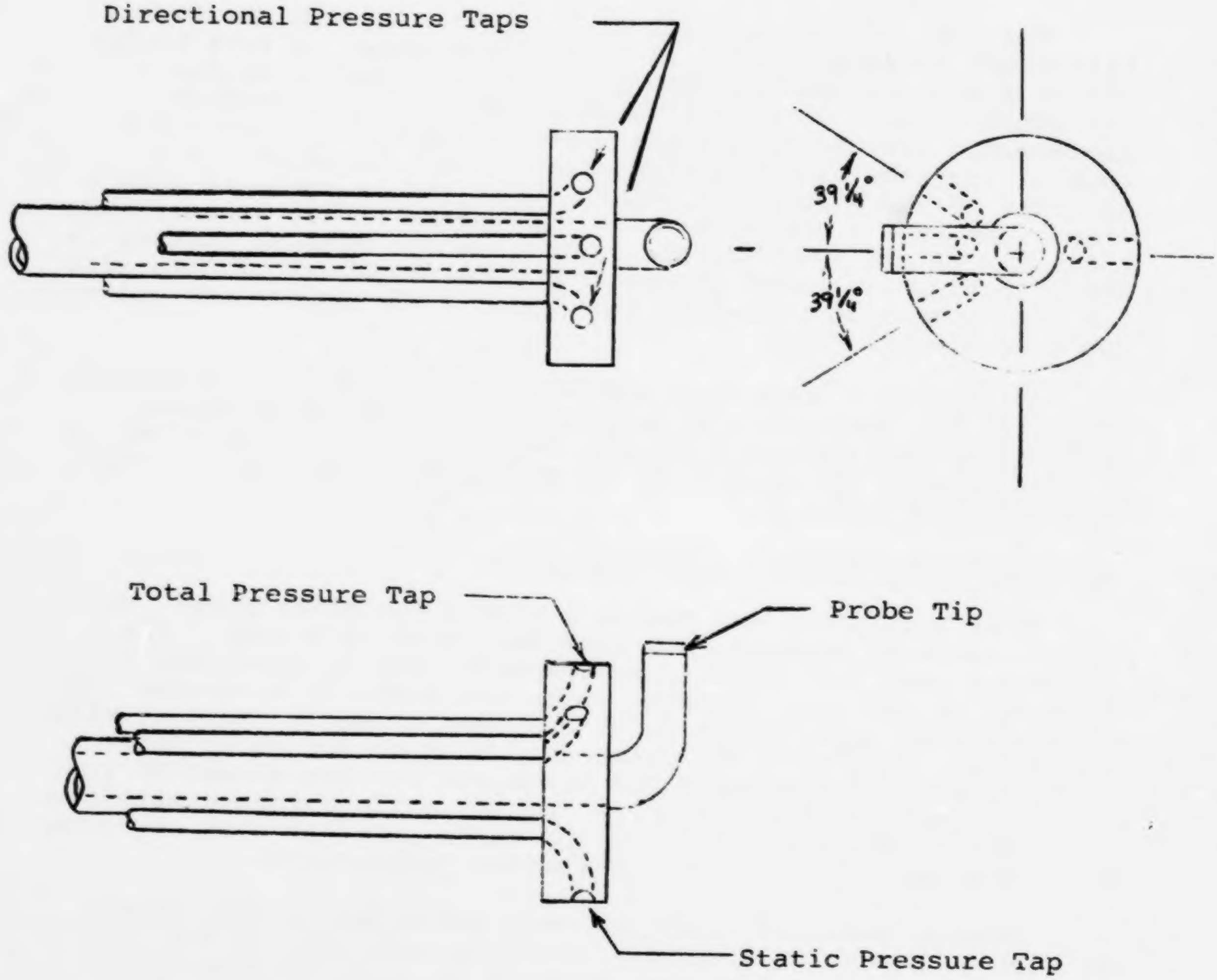

Directional Pressure Taps
39¼°
39¼°
Total Pressure Tap
Probe Tip
Static Pressure Tap

Figure 61. Connecticut State Department of Environmental Protection probe (Ref. 54)

1. Properly accounting for the presence of cyclonic flow, and

2. collecting and accounting for the liquid present in droplet form.

Development of techniques and instrumentation which address these two problems was the basic goal of the field testing and laboratory model testing programs outlined in the following.

PRELIMINARY FIELD TESTS

The site chosen for initial field testing was the Seneca Wastewater Treatment Plant in Eagan, Minnesota. A twin incinerator system is used at this plant to burn sewage sludge collected through water treatment processes. Two Peabody impingement tray scrubbers are used for particulate emission control from the sludge incinerators. Each scrubber has a capacity of 340 m^3/min (12,000 ft^3/min) and is equipped with a fixed vane type centrifugal mist eliminator at the exhaust end. A diagram of the wet scrubber system and the exhaust ducting is shown in Fig. 62. Impingement tray type scrubbers of this size are very common in industry, particularly in particulate collection from incinerators.

A total of 5 days were spent in performing the preliminary field tests. Velocity and particulate concentration measurements were made through existing sample ports located at points B and C in Fig. 62 as well as in additional sample ports which were added at point A.

Velocity Measurements - Cyclonic Flow

Flow angularity was measured with a Fecheimer probe, while actual velocity measurements were made with an S-tube. The procedure used for velocity measurements was to first conduct a traverse of the duct with the Fecheimer probe to determine the flow angle at each sample point and then traverse the duct with the S-tube, orienting the probe according to the angle determined from the Fecheimer probe traverse. A flow direction tuft was also used to visually check the yaw angle measured with the Fecheimer probe. In all cases the angle observed with the flow direction tuft confirmed the Fecheimer indications.

Several velocity traverses were performed in this manner at each of the three sampling locations indicated in Fig. 62. Pronounced cyclonic flow was observed at point A, just downstream of the scrubber exhaust. Yaw angles as large as 75° and swirl velocities as high as 20 m/sec were observed at this location. Typical profiles of the velocity and the axial velocity component measured at point A are shown in Fig. 63. The degree of cyclonic flow was somewhat reduced at point B,

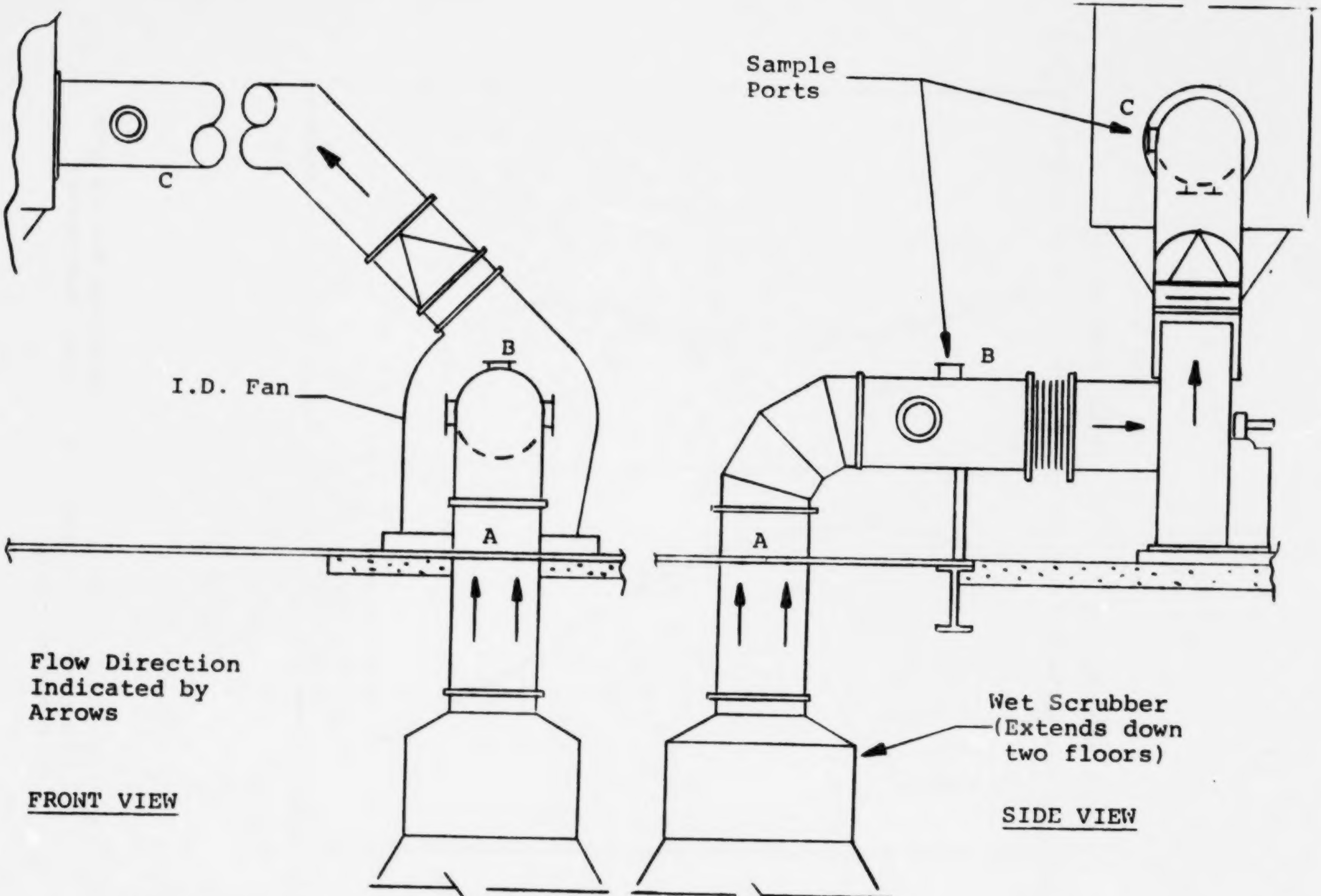

C
C
Sample
Ports
B
B
I.D. Fan
A
A
Flow Direction
Indicated by
Arrows
FRONT VIEW
Wet Scrubber
(Extends down
two floors)
SIDE VIEW

Figure 62. Wet scrubber and exhaust ducts at the Seneca Wastewater Treatment Plant - Eagan, Minnesota

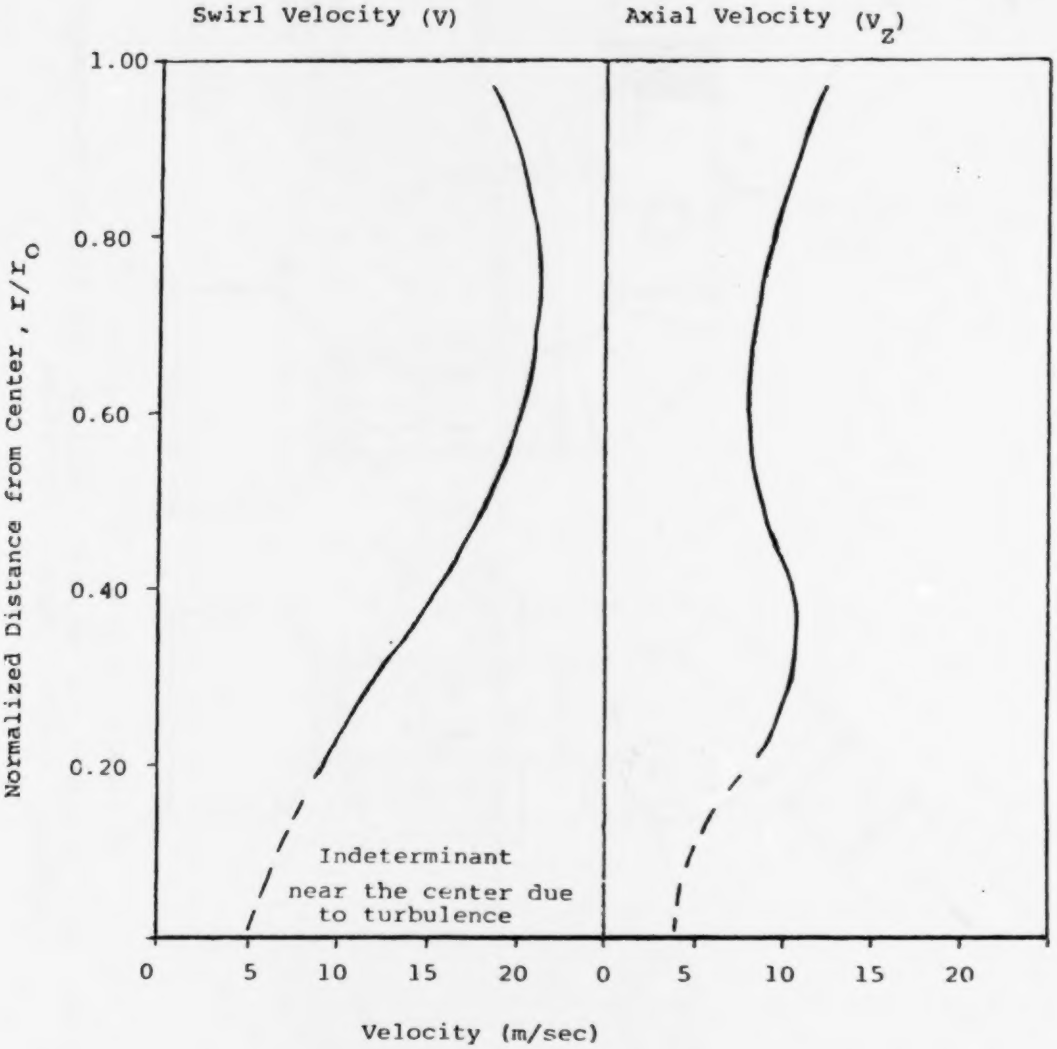


Figure 63. Typical velocity profile obtained during preliminary field tests at Seneca Wastewater Treatment Plant

the maximum yaw angle and velocity being approximately 60° and 17 m/sec. The flow downstream of the ID fan, at point C in Fig. 62, was nearly uniform in direction. When the axial component of velocity was used to compute the volumetric flow rate through the scrubber exhaust ducting, the measured flow rates at points A and C agreed to within 6%, indicating the basic validity of this method of velocity determination for cyclonic flow of the type observed in this field application.

Particulate Sampling - Liquid Droplets

The sampling equipment assembled for the preliminary field tests included the basic components of a standard EPA Method 5 sampling train: a glass lined, heated probe and attached S-tube, a filter holder, two wet and two dry impingers, a condenser, silica gel dessicant, a vacuum pump, a dry gas meter, and a rotameter. Particulate concentration measurements were made at all three of the sample port locations indicated in Fig. 62. The sample probe was oriented at the yaw angle determined by the Fecheimer probe at each traverse point, and an isokinetic sampling rate was set according to the velocity indicated by the S-tube.

Although the duct walls were wetted at locations A and B, few droplets were visually observed in the sampling train. At point C, however, liquid droplets were present to such a degree as to thoroughly wet the sampling probe. Large pressure drops in the sampling train developed quickly as droplets built up on the filter mats and the vacuum pump was not able to maintain the required isokinetic sampling rate. This forced sampling times to be kept very short.

An illustration of the difference in droplet concentrations at points B and C was obtained by using an in-stack filter to collect particulate samples at each location. Filters inserted at each location are shown in Fig. 64. It can be seen that the filter deployed upstream of the ID fan is much more uniform in density of collected particulate than the downstream filter. The uneven appearance of the downstream filter may be due to the presence of particulate contained in or on the surface of liquid droplets. The variation in droplet concentration is likely due to the cyclonic flow field; entrained droplets leaving the scrubber are driven to the duct walls and pass in a film near the walls into the ID fan. The droplets are then evenly distributed and reentrained by the flow leaving the fan.

A liquid droplet precutter designed and fabricated by FluiDyne was added to the sampling train in an attempt to collect the sampled liquid droplets. The precutter is shown in Figs. 65 and 66. The designed droplet cut diameter for this inertial separator was 10 μm. Use of the precutter in further

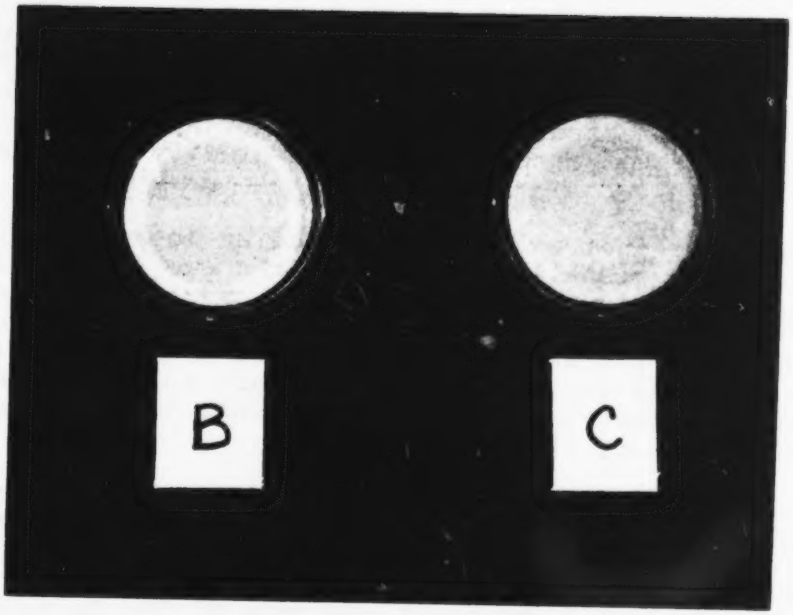


Figure 64. Filter samples taken at the Seneca Wastewater Treatment Plant during preliminary field tests

B = Upstream of I.D. fan

C = Downstream of I.D. fan

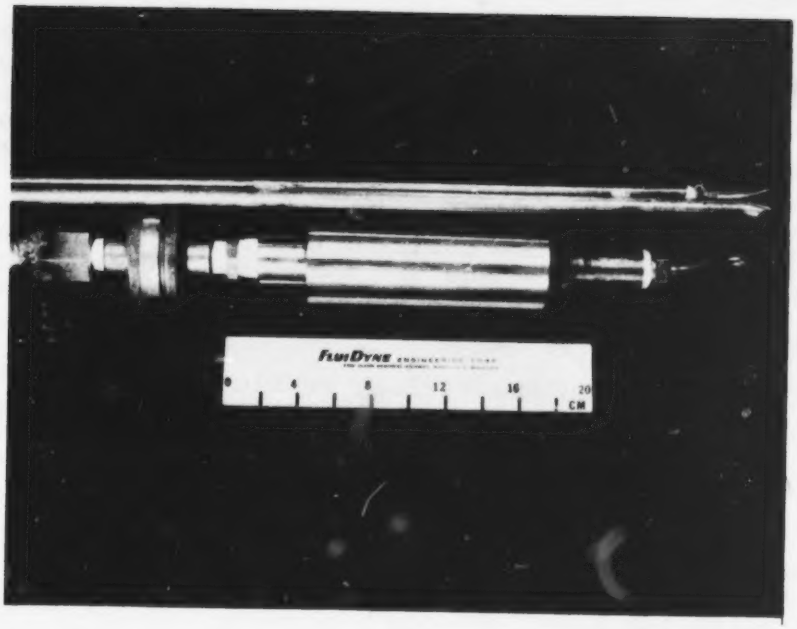

FLUIDYNE ENGINEERING CORP
0
4
8
12
16
20
CM

Figure 65. Inertial separation precutter used in preliminary field tests at Seneca Wastewater Treatment Plant

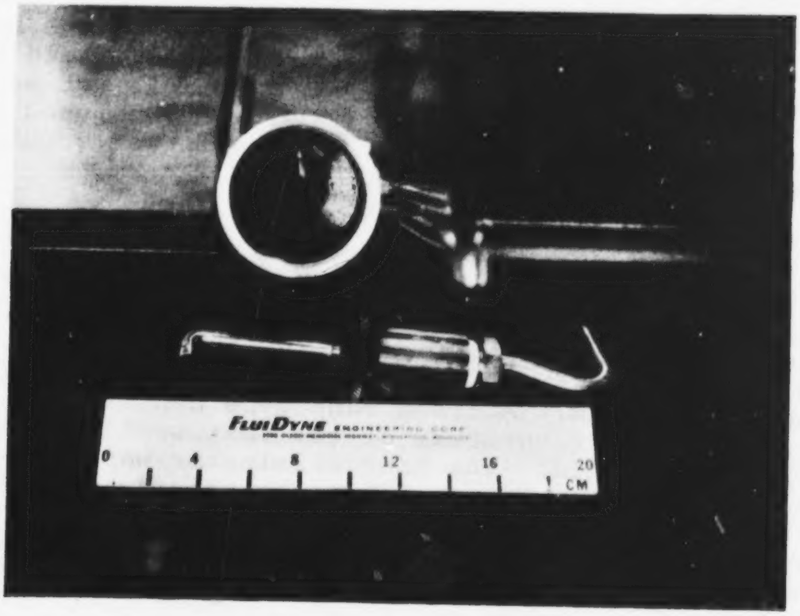

FLUIDYNE ENGINEERING CORP
0
4
8
12
16
20
CM

Figure 66. Internal view of inertial separation precutter

particulate sampling eliminated the pressure buildup due to droplets on the filters. When the precutter was opened after sampling, however, no liquid was found, although some particulate matter was present.

When the water vapor content of the scrubber exhaust stream was measured with a dewpoint indicator, (Alnor Model 7000 V) the stream was found to have a relative humidity of only 79%. Thus, it was concluded that liquid droplets which were collected in the precutter were evaporated by the sample flow, since the gas stream was not saturated. This interesting finding leads to the conclusion that one should not assume a saturated stream on the basis of observed liquid droplets, as is suggested in EPA Method 5. Large discrepancies in total water vapor content calculated from dewpoint measurements and with the Method 5 calculation were also observed in Ref. 55.

In addition to the various problems described above, the particulate concentrations measured in the preliminary field tests varied considerably. These measurements are summarized in Table 12. The wide variation emphasizes the basic difficulty in obtaining reliable particulate concentration measurements in the scrubber exhaust stream. Some of the unreliability may be related to the amount of particulate matter lost in the sample probe due to impingement and settling of water droplets, even though the probe was cleaned according to Method 5 procedures. After one series of tests, the particulate matter collected in probe washing amounted to 13% of the total particulate matter collected.

MODEL STUDIES

A model studies program was developed on the basis of the information obtained through the preliminary field tests. A laboratory model of the exhaust of a typical wet scrubber was designed and fabricated. This model was then used to evaluate techniques and instrumentation for use in wet scrubber emission measurements.

Model Design and Fabrication

The laboratory model, shown schematically in Fig. 67, was constructed at FluiDyne's Medicine Lake Laboratory. A liquid droplet injection system located in the horizontal air supply ductwork provided the simulation of entrained liquid droplets in the flow stream. A fixed vane type centrifugal mist eliminator located just upstream of the test section produced a cyclonic flow field. The mist eliminator was purchased from Peabody Engineering Corporation, the manufacturer of the scrubbers used at the preliminary field test site. The mist eliminator is a scaled-down version of those used for separation of entrained droplets in the scrubber exhaust at the Seneca

TABLE 12. PARTICULATE CONCENTRATION MEASUREMENTS FROM PRELIMINARY FIELD TESTS

Sample Location (See Figure 62)	A	B	C
Particulate Concentration Measurements without Droplet Precutter in Sample Train (mg/Nm^3)	-	97	61
Particulate Concentration Measurements with Droplet Precutter in Sample Train (mg/Nm^3)	100 56	-	41

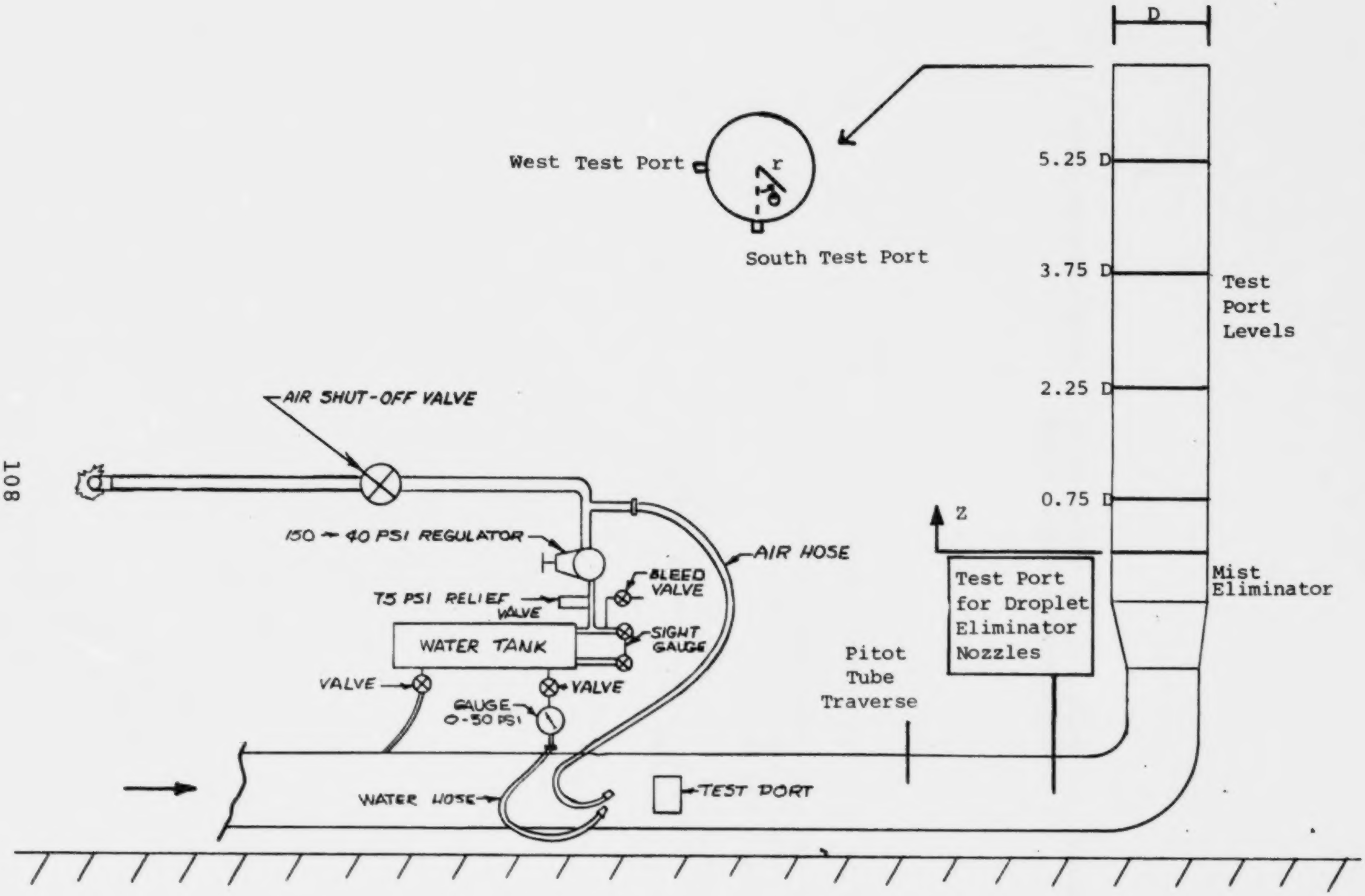

D
West Test Port
r
South Test Port
5.25 D
3.75 D
Test
Port
Levels
2.25 D
0.75 D
Z
Mist
Eliminator
Test Port
for Droplet
Eliminator
Nozzles
Pitot
Tube
Traverse
AIR SHUT-OFF VALVE
150 ~ 40 PSI REGULATOR
AIR HOSE
BLEED
VALVE
75 PSI RELIEF
VALVE
SIGHT
GAUGE
WATER TANK
VALVE
VALVE
GAUGE
0-50 PSI
WATER HOSE
TEST PORT

Figure 67. Schematic of scrubber exhaust model

Treatment Plant. Two sample ports were installed at each of four levels downstream of the mist eliminator in the test section as indicated in Fig. 67. A platform was constructed to provide access to the test section sample ports, as shown in Fig. 68.

The droplet injection system is pictured in Figs. 69-72. Three spray nozzles inject water into the flowing air stream at a rate which can be controlled by adjusting the water pressure, the atomizing air pressure, and needle valves inserted in the spray nozzles. The nozzles were directed such as to fill the duct uniformly with water droplets, as determined by visual observation.

Flow Velocity Studies

The main objective of the velocity studies in the scrubber exhaust model was to assess the ability of various instruments to determine the volumetric flow rate and the flow angularity in the cyclonic flow field. Three instruments were used to make velocity measurements in the model; a standard S-tube, a three dimensional directional pitot probe, and a Fecheimer type probe.

The S-tube, attached to a standard EPA Method 5 type sampling probe, was first used to assess the error level which would exist if this instrument were simply oriented parallel to the duct centerline without accounting for the cyclonic nature of the flow field. Several 12 point velocity surveys were made with the S-tube, traversing the duct as if the flow were uniformly parallel to the duct centerline, and the volumetric flow rate determined from these traverses was compared with the actual volumetric flow rate through the model as determined from pitot tube traverses in the horizontal air supply ductwork upstream of the test section. The results of these surveys, shown in Fig. 73, show that the error is on the order of 60% to 115% of the actual flow rate and that the error actually increases from 2 to 6 duct diameters downstream of the mist eliminator, after an initial decrease.

Attempts were made to determine the yaw angle of the flow by using the demonstrated directional sensitivity of an S-tube as indicated in Fig. 56. However, the turbulent fluctuations in the flow caused fluctuations in the S-tube output of such magnitude as to completely overshadow the capability of this instrument to locate the angle of maximum velocity. Thus, the S-tube could not be used with any degree of reliability to determine the yaw angle in cyclonic flow in this manner. A potential method for use with the S-tube which was not evaluated is the so called "null method," in which the S-tube is rotated until the pressure sensed by the two pressure taps is equal. The instrument should then be aligned at 90° to the

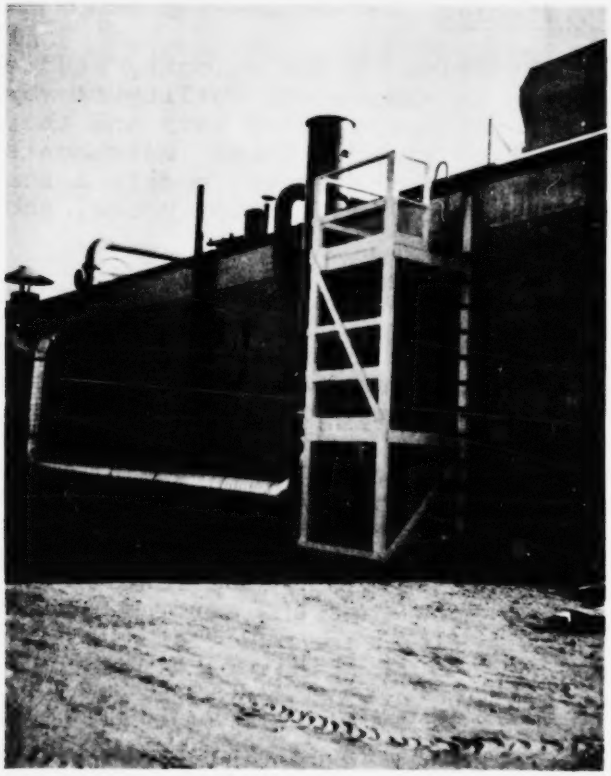


Figure 68. Scrubber exhaust model and test platform at Medicine Lake Laboratory

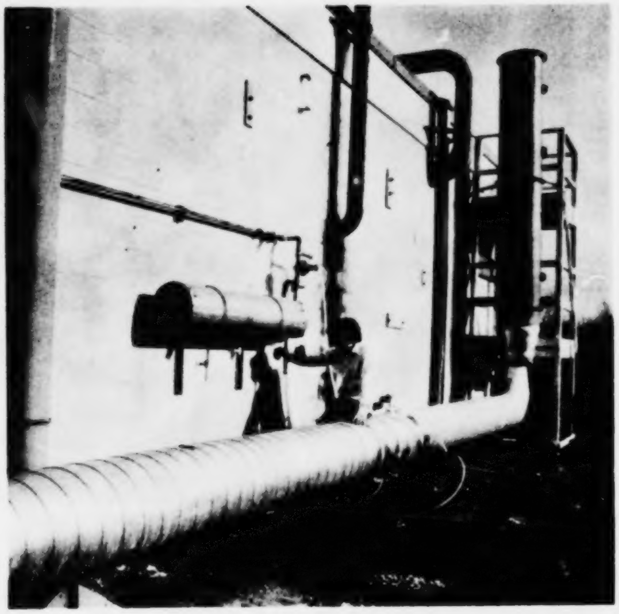


Figure 69. Droplet injection system for scrubber exhaust model-external hardware

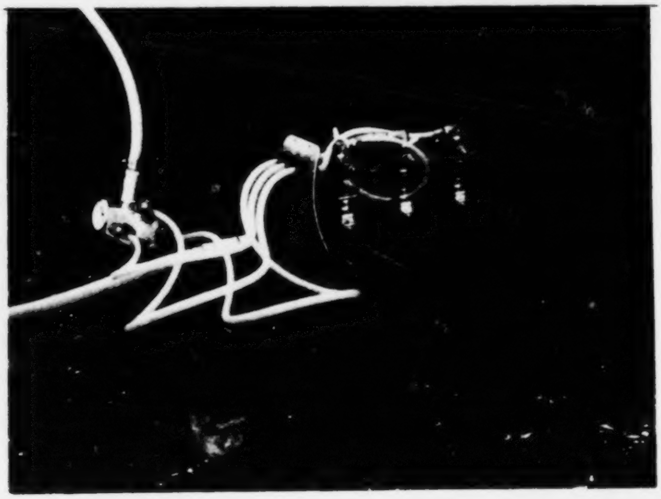


Figure 70. Spray nozzles for droplet injection system (removed from ductwork of scrubber exhaust model)

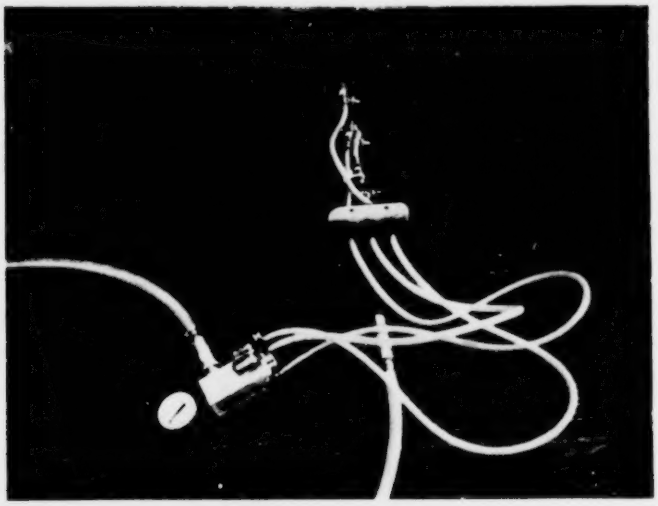


Figure 71. Droplet injection system spray nozzles producing low droplet density mist

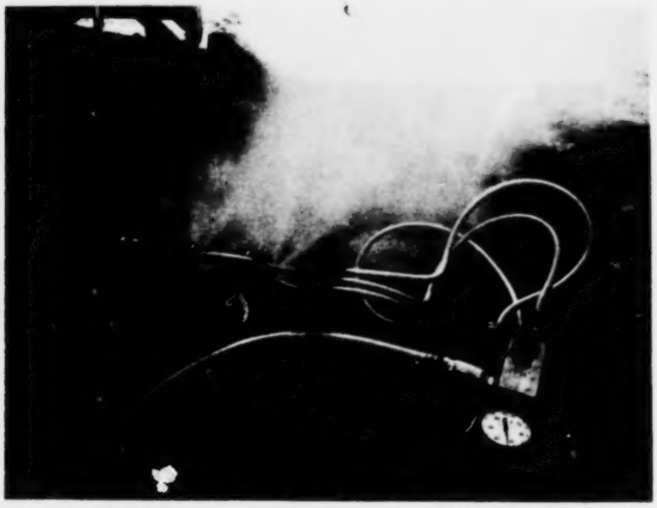


Figure 72. Droplet injection system spray nozzles producing high droplet density mist

V_m = measured volumetric flow rate

V_a = actual volumetric flow rate

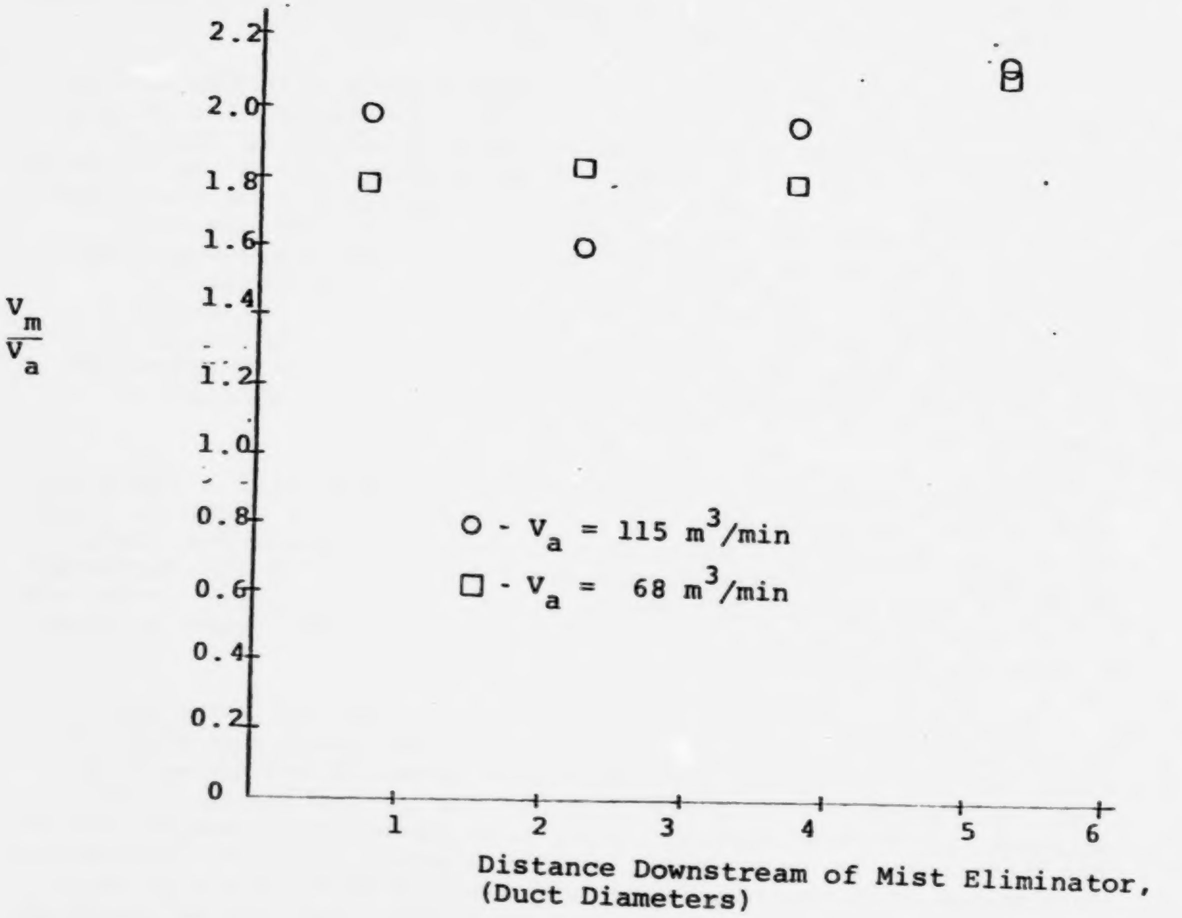


Figure 73. Volumetric flow rate error for 12-point velocity surveys in scrubber exhaust model with S-tube parallel to duct centerline

velocity and can be rotated so as to be properly aligned for a velocity measurement.

Extensive surveys of the cyclonic flow field were made with a directional velocity probe capable of accurately measuring both pitch and yaw angles as well as the flow velocity. This instrument, the United Sensor DC-125 directional velocity probe, is shown in Figs. 74 and 75 together with a duct traverse unit which was used to accurately position the probe in the test section of the scrubber exhaust model. As can be seen in Fig. 75, the pressure taps on this probe are very small, thus making use of the instrument impractical in particulate-laden streams. It was used in the model, however, to obtain an accurate map of the flow field for evaluation of other velocity instruments. This probe mounted in the scrubber exhaust model is shown in Fig. 76. Manufacturer's calibration data were used to reduce the probe measurements to velocites.

The results of the velocity measurements with the United Sensor probe are shown in Figs. 77-80. The definition of the coordinates used in presenting the data is shown in Fig. 67. The actual flow rate, Q_a, used to nondimensionalize the velocity terms in Figs. 77-80, was determined from pitot tube traverses in the horizontal air supply ductwork upstream of the test section. The curves indicated in Figs. 77-80 represent intuitive estimates of the "average" data and are not based on curve-fitting or regression formulas. The most interesting observation made from these velocity surveys is the fact that the average radial velocity component is very small, particularly as the distance downstream of the mist eliminator increases.

Extensive velocity surveys were also made with a Fecheimer type probe, shown in Fig. 81. The traverse unit shown in Figs. 74 and 76 was used to position the Fecheimer probe for these measurements. The same points were measured with the Fecheimer probe as with the United Sensor probe. The Fecheimer probe was calibrated against a standard pitot tube and was found to have a velocity coefficient of 1.06.

Velocity components determined from the yaw angle and total velocity measured with the Fecheimer probe are shown in Figs. 82-85. The same dimensionless presentation is used as for the United Sensor probe. While the United Sensor probe appears to provide somewhat more repeatable data, comparison of the measurements indicates that the average velocity components determined with the two instruments agree quite closely, with the exception of the radial component which can not be measured with the two-dimensional Fecheimer probe. Since the radial components indicated in Figs. 77-80 are essentially negligible, however, the approximation made in using the two-dimensional instrument seems to be acceptable.

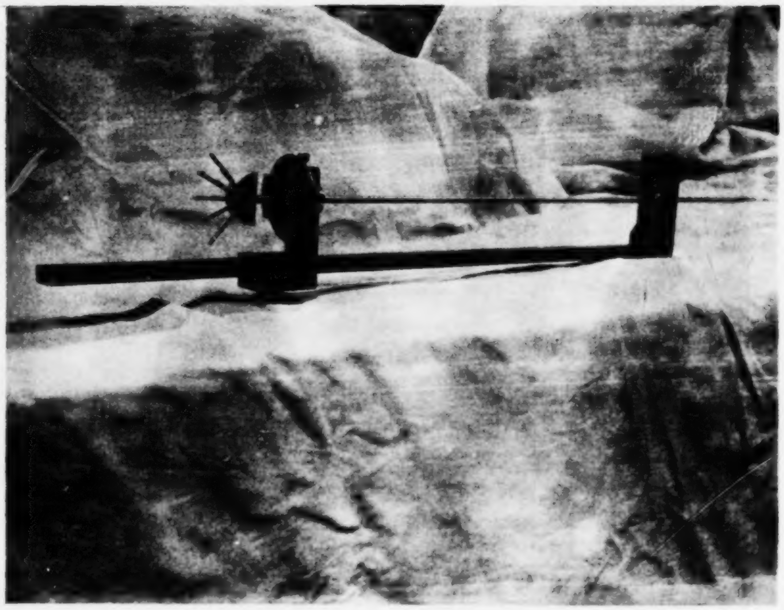


Figure 74. United sensor DC-125 3-dimentional directional probe and traverse unit

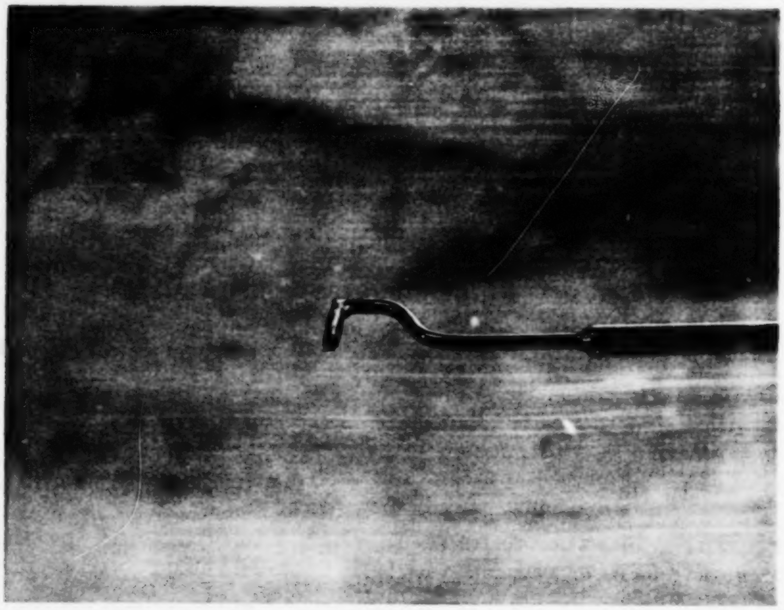
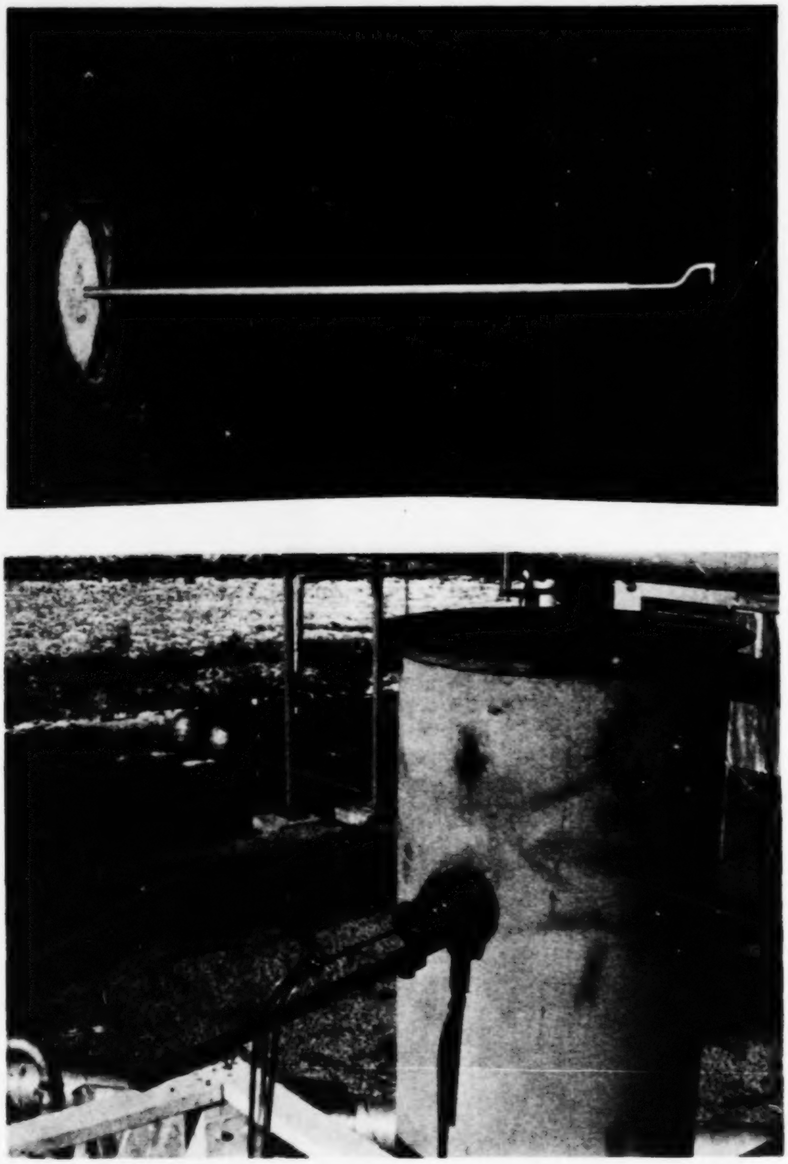


Figure 75. Sensing head of united sensor DC-125 directional probe



INTERNAL
VIEW

EXTERNAL
VIEW

Figure 76. United sensor DC-125 directional probe mounted in scrubber exhaust model for velocity traverses

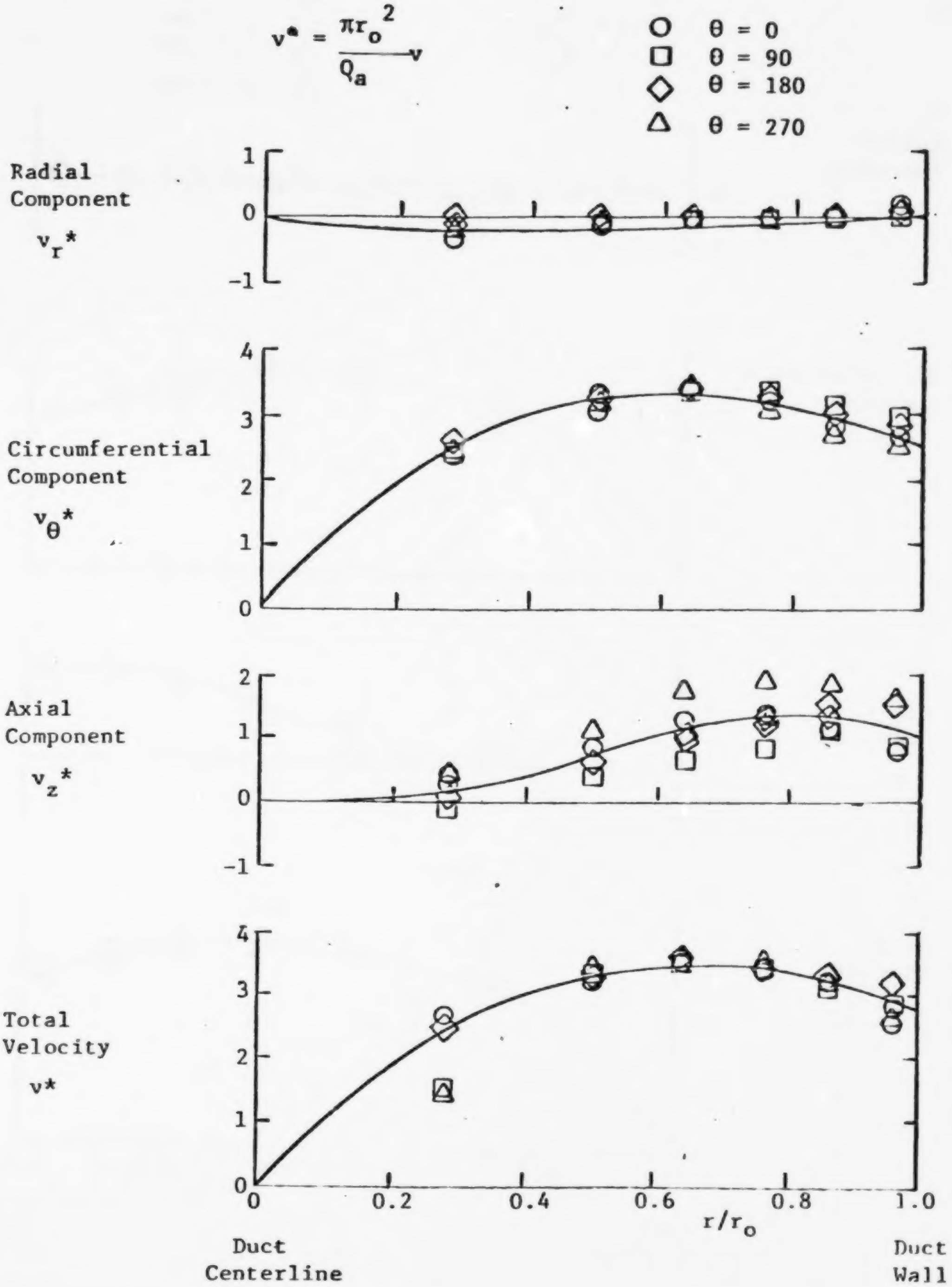


Figure 77. Normalized velocity components measured 0.75 duct diameters downstream of mist eliminator - United sensor probe

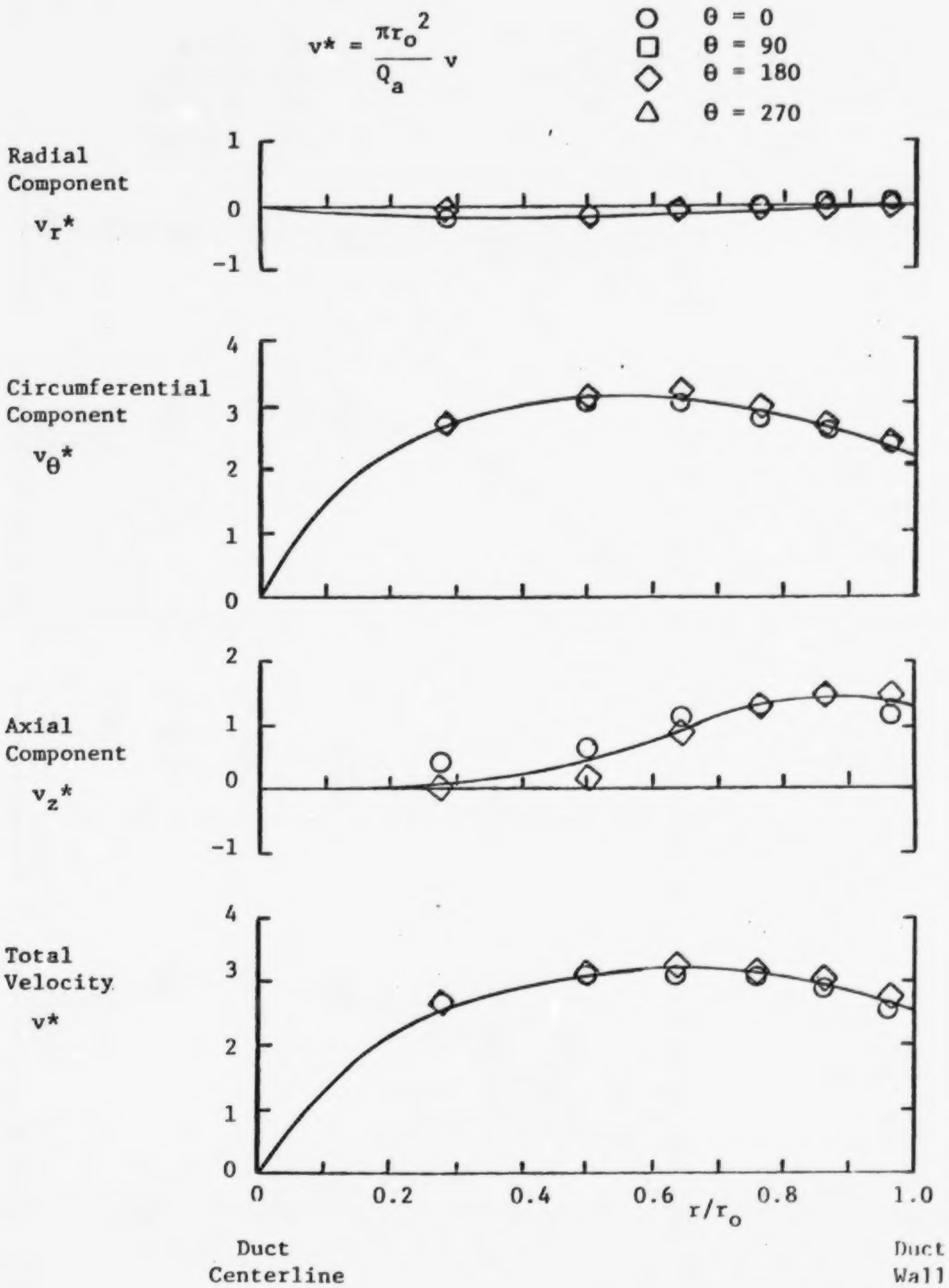


Figure 78. Normalized velocity components measured 2.25 duct diameters downstream of mist eliminator - United sensor probe

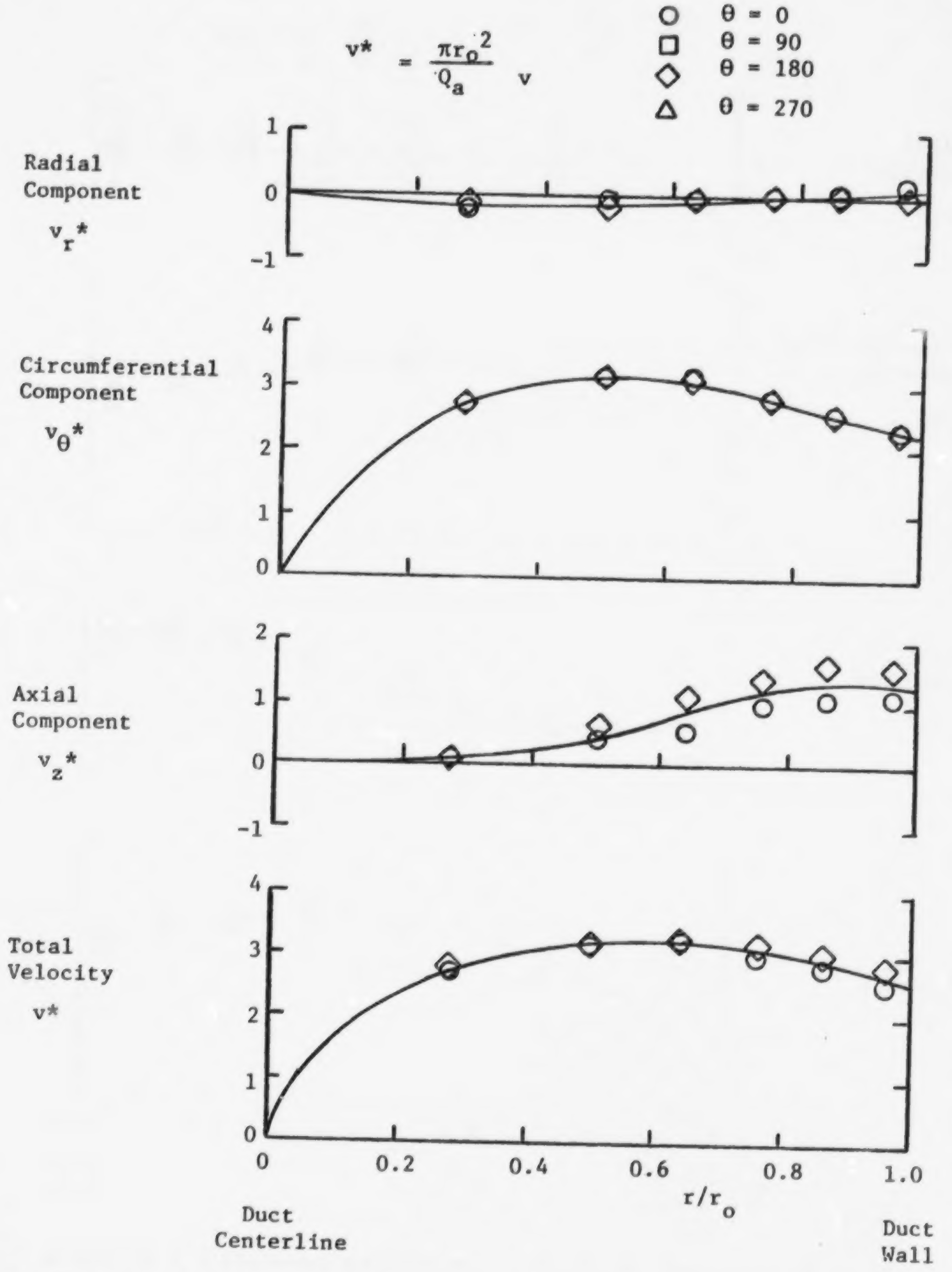


Figure 79. Normalized velocity components measured 3.75 duct diameters downstream of mist eliminator - United sensor probe

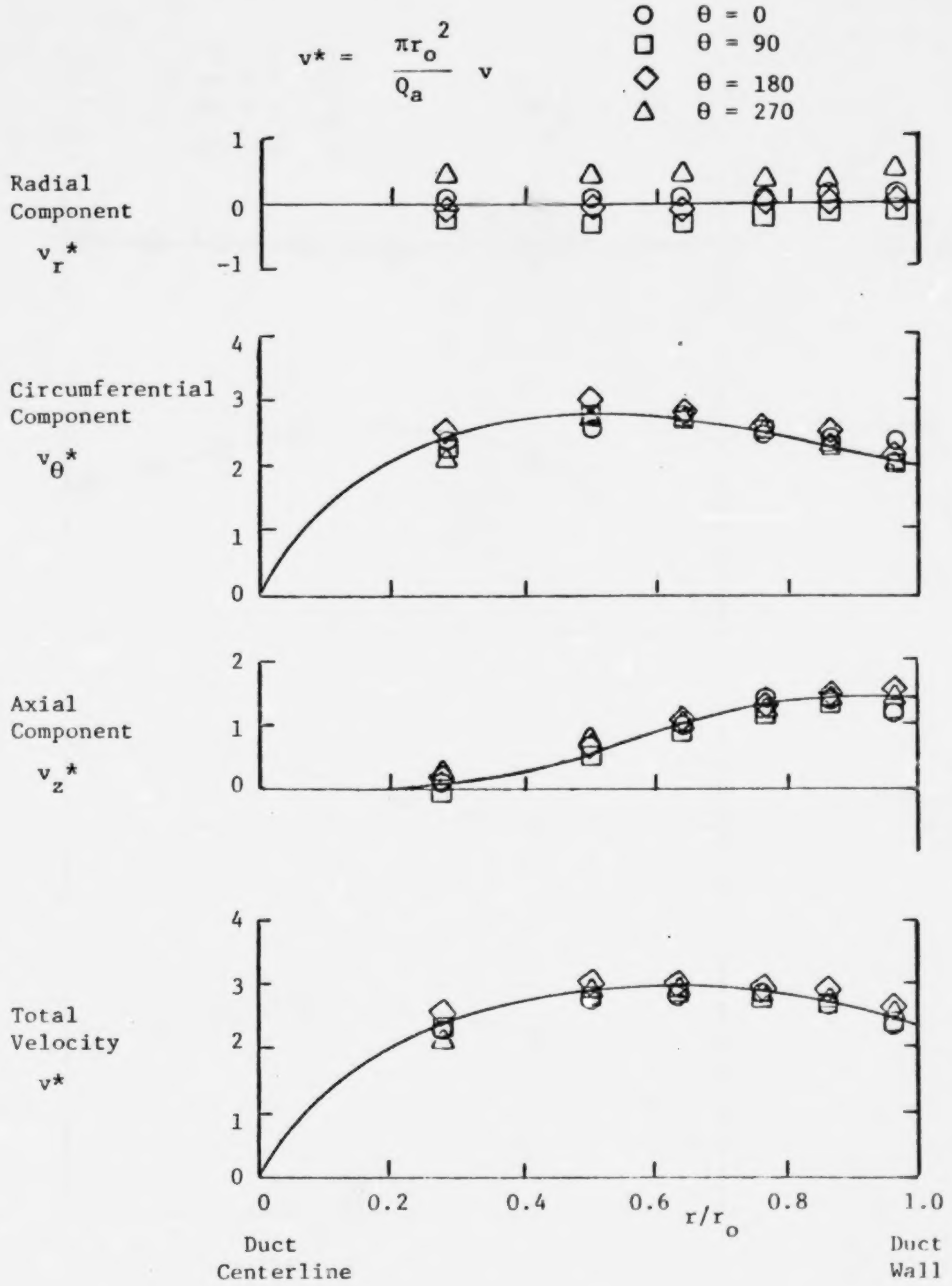


Figure 80. Normalized velocity components measured 5.25 duct diameters downstream of mist eliminator - United sensor probe

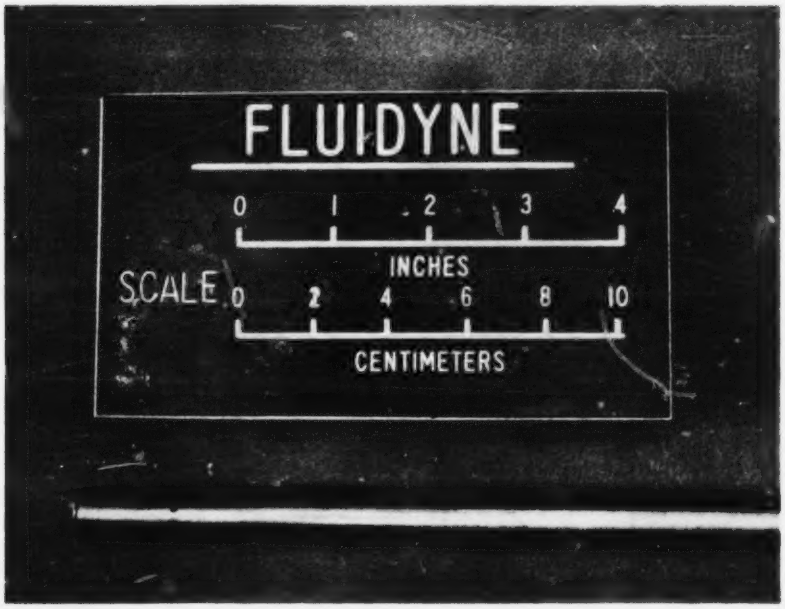

FLUIDYNE
0
1
2
3
4
INCHES
SCALE
0
2
4
6
8
10
CENTIMETERS

Figure 81. Fecheimer probe used in velocity surveys of scrubber exhaust model

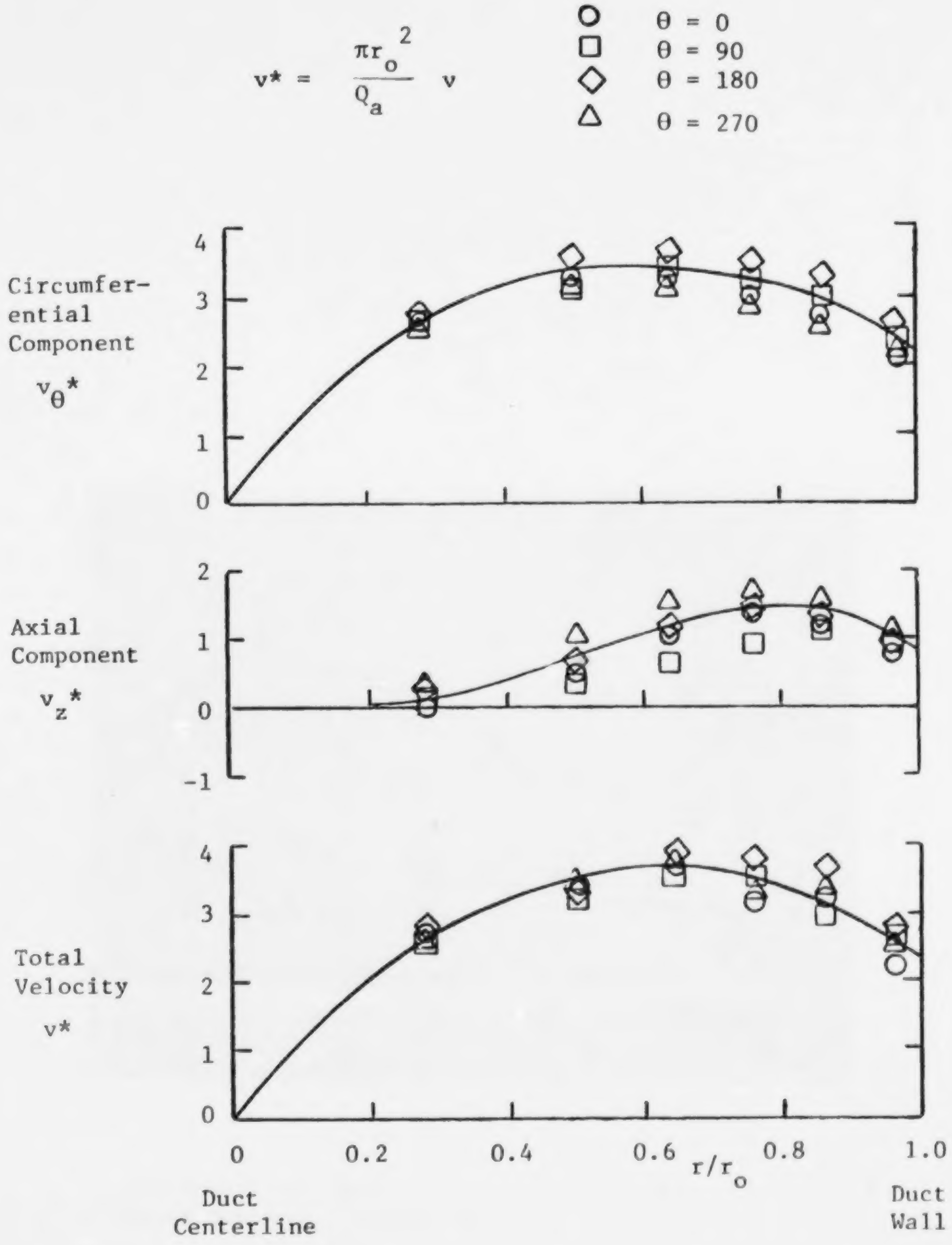


Figure 82. Normalized velocity components measured 0.75 duct diameters downstream of mist eliminator - Fecheimer probe

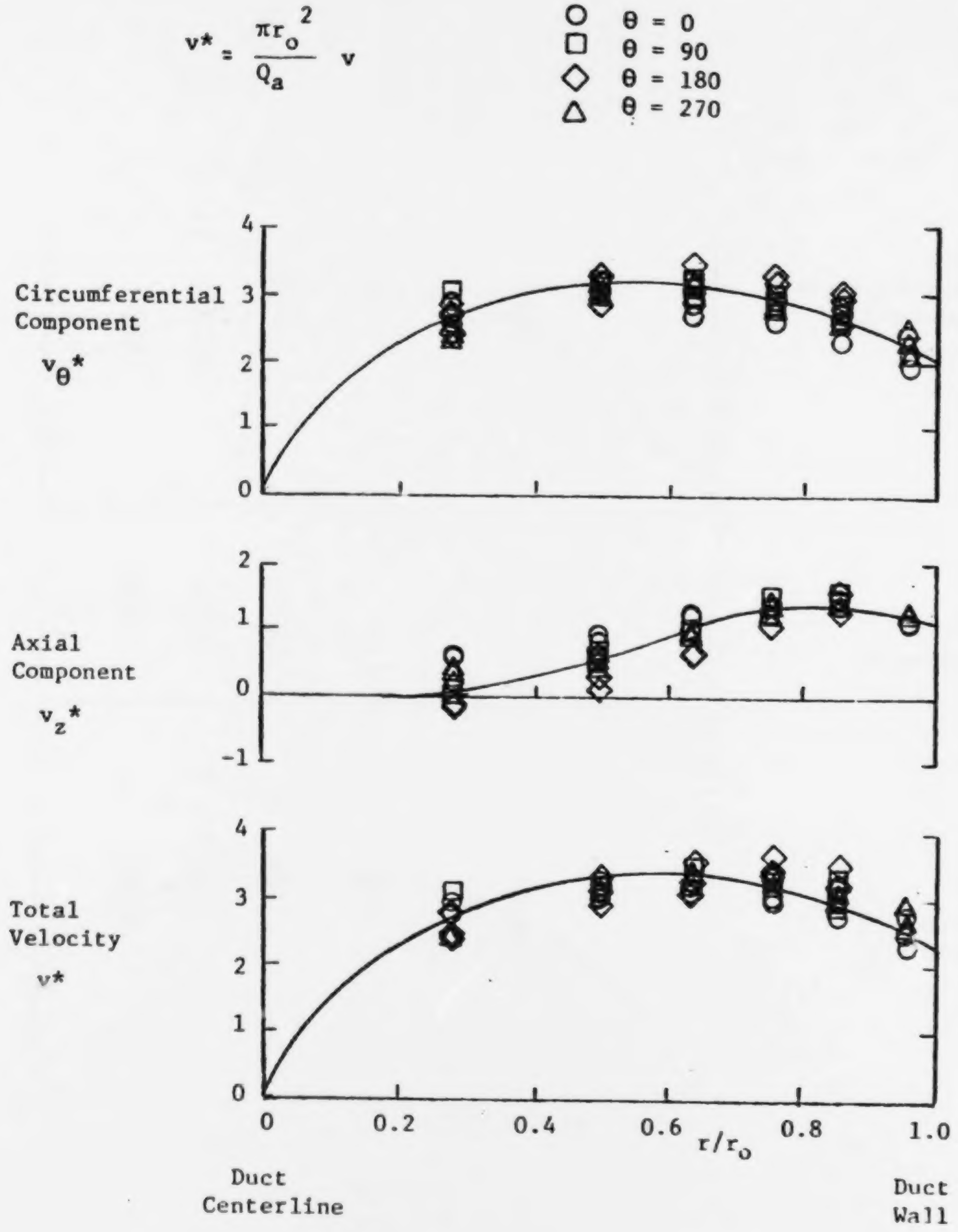


Figure 83. Normalized velocity components measured 2.25 duct diameters downstream of mist eliminator - Fecheimer probe

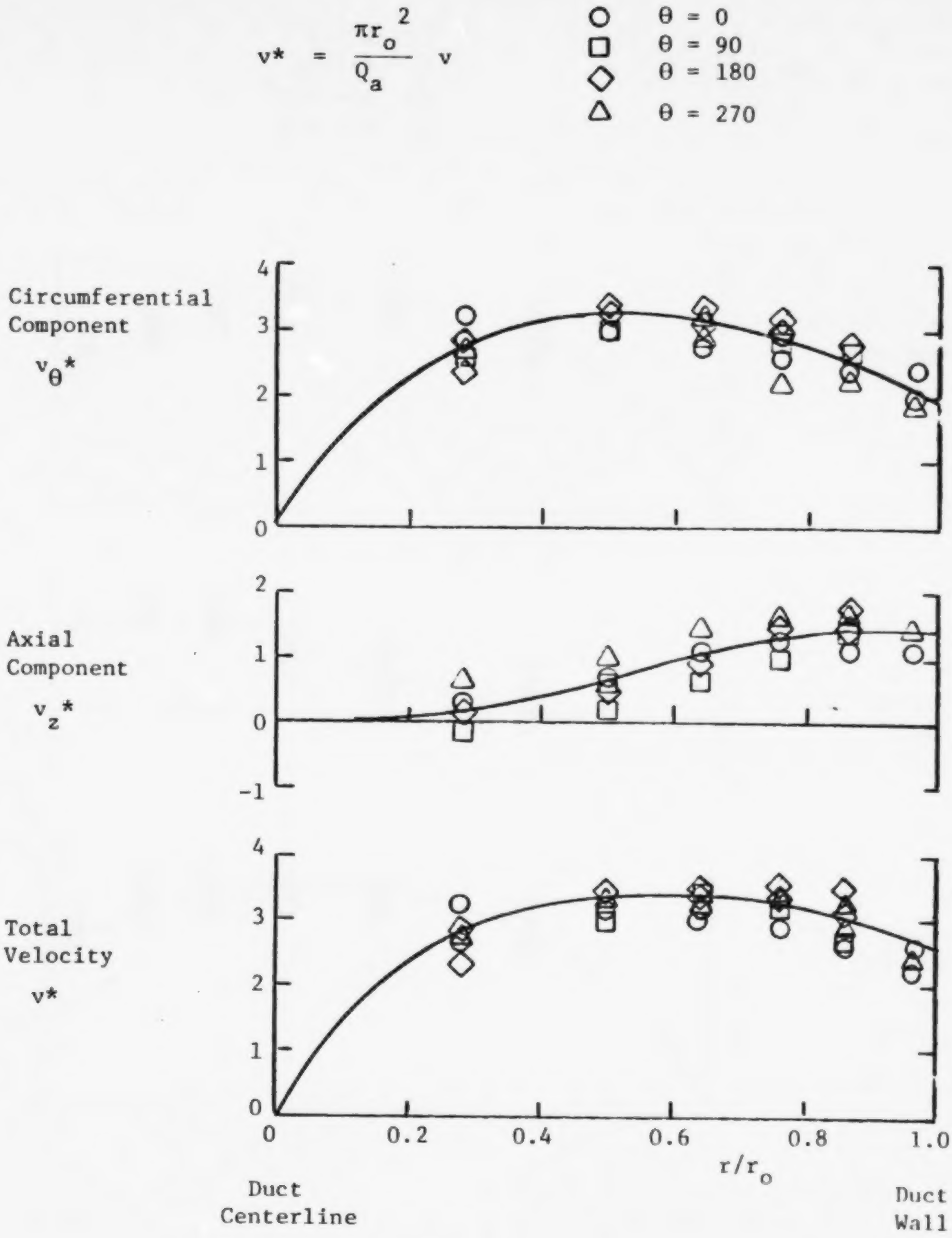


Figure 84. Normalized velocity components measured 3.75 duct diameters downstream of mist eliminator - Fecheimer probe

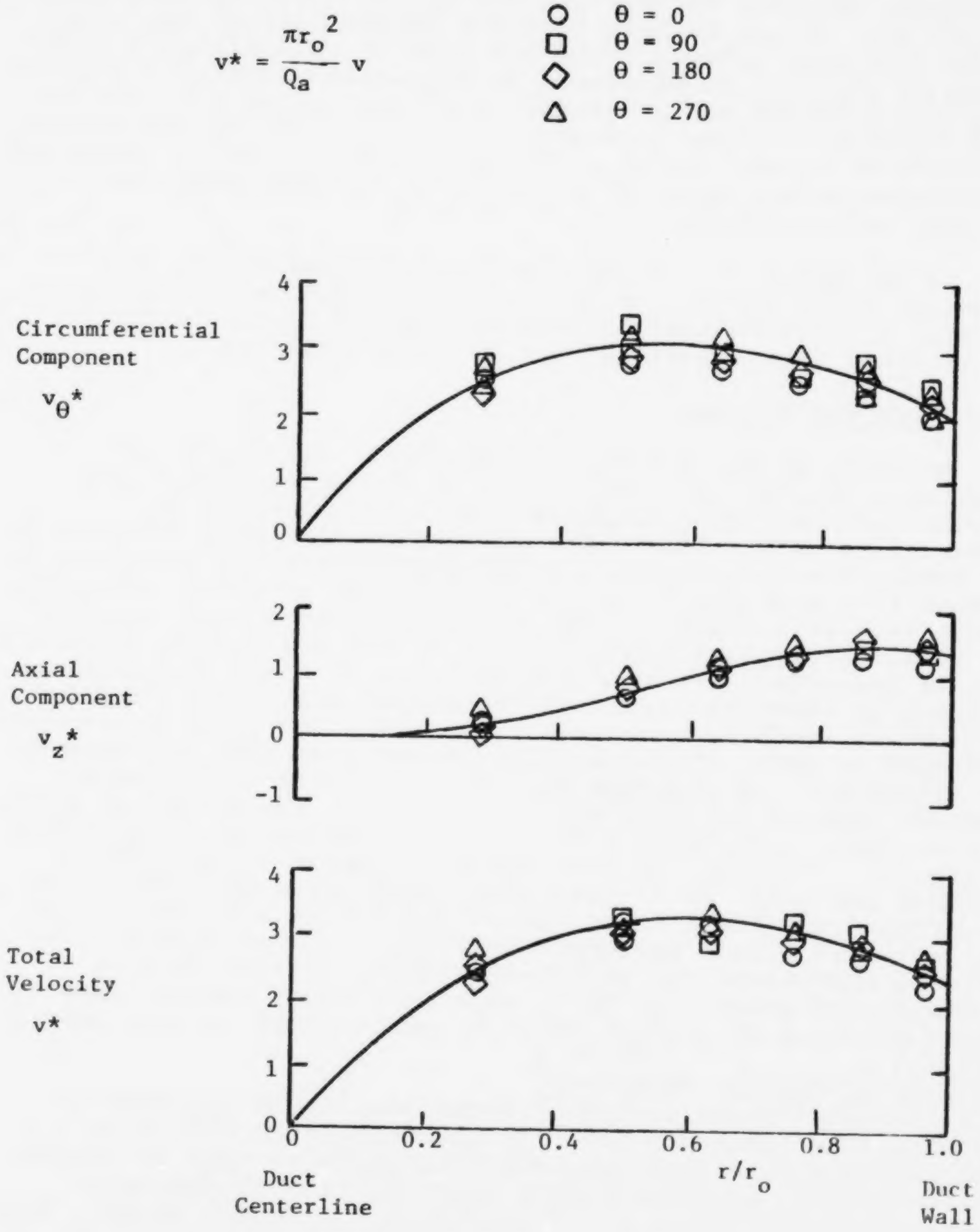


Figure 85. Normalized velocity components measured 5.25 duct diameters downstream of mist eliminator - Fecheimer probe

The degree of accuracy of the Fecheimer probe in determining total volumetric flow rate was also examined. Comparisons of flow rates determined from the axial velocity component in several 24-point surveys and the actual flow rate are shown in Fig. 86. It can be seen that the reliability of the volumetric flow rate surveys increased greatly with distance downstream of the mist eliminator. At the maximum distance achieved in the scrubber exhaust model, 5.25 duct diameters, the 24-point surveys provided accuracy within 5% of the actual value. At locations closer to the mist eliminator, a greater number of measurement points would be required to achieve sufficient accuracy and repeatability.

On the basis of the information presented above, the Fecheimer probe appears to be a suitable instrument for determination of both volumetric flow rate and flow angularity in the cyclonic flow typical of wet scrubber outlets.

Liquid Droplet Studies

As outlined previously, the principal difficulty in sampling a droplet-laden stream is to properly collect and account for the liquid droplets. This is important for a number of reasons. First, the collection of liquid droplets by the sample train is critical since particulate may generally be present in the droplets, either in solution or merely adhering to the droplet surfaces. Thus in order to adequately measure the total particulate concentration in the gas stream, droplets must be collected. Second, the humidity of a gas stream must be known in order to calculate the proper isokinetic sampling rate. Since humidity measurements in a droplet-laden stream are difficult to make, it is usually assumed that such gas streams are saturated. As observed in the preliminary field tests, however, this is not necessarily the case. The potential error in isokinetic rate arising from this assumption is illustrated in Fig. 87. Finally, in some cases a droplet concentration gradient may exist in a given flow field, also as observed in the preliminary field tests, which results in a difference in the amount of liquid present at various sampling points. In order to understand the potential effects of such droplet concentration gradients, being able to account for the mass of liquid droplets at a given sampling point would be very useful.

Analysis of Droplet Motion--

Analysis of the motion of entrained liquid droplets in cyclonic flow indicates that the characteristic situation consists of a core region of the duct which is free of liquid droplets and an ever increasing concentration of droplets nearer to the duct wall, as observed at the Seneca plant. This was demonstrated by an analysis of droplet motion based on the velocity field measured in the scrubber exhaust model. In the following, the coordinate directions are defined as shown in

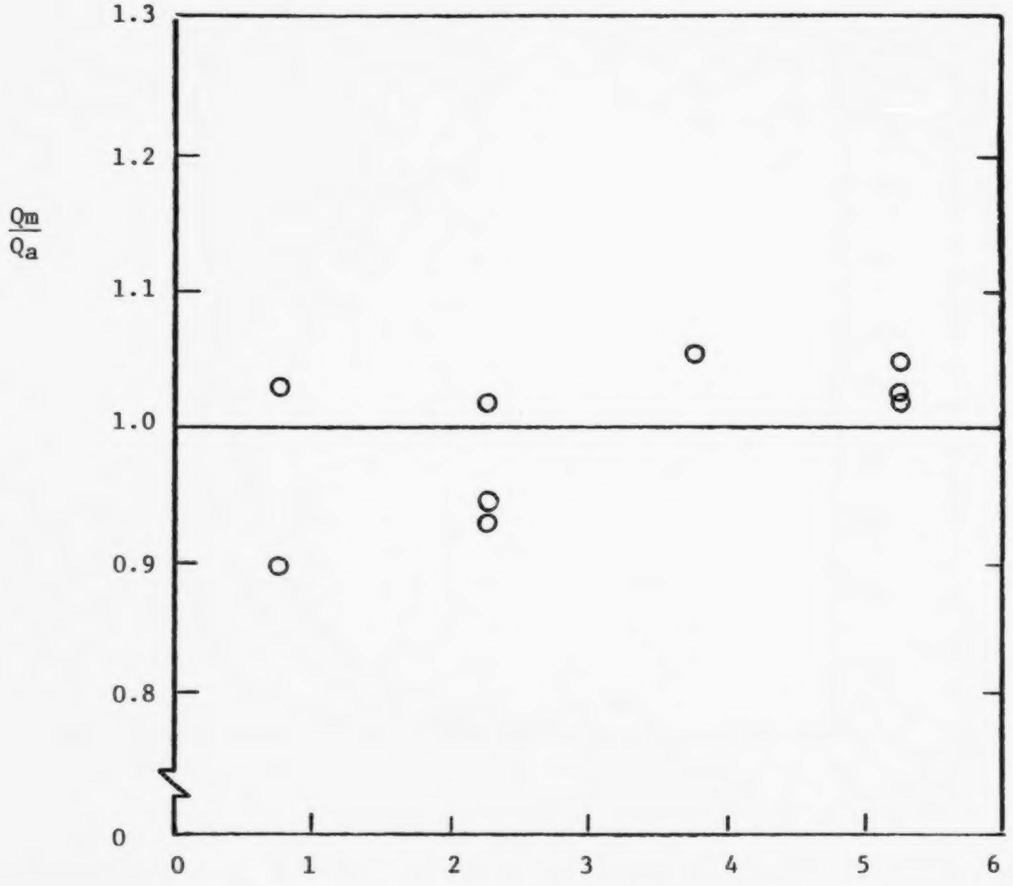
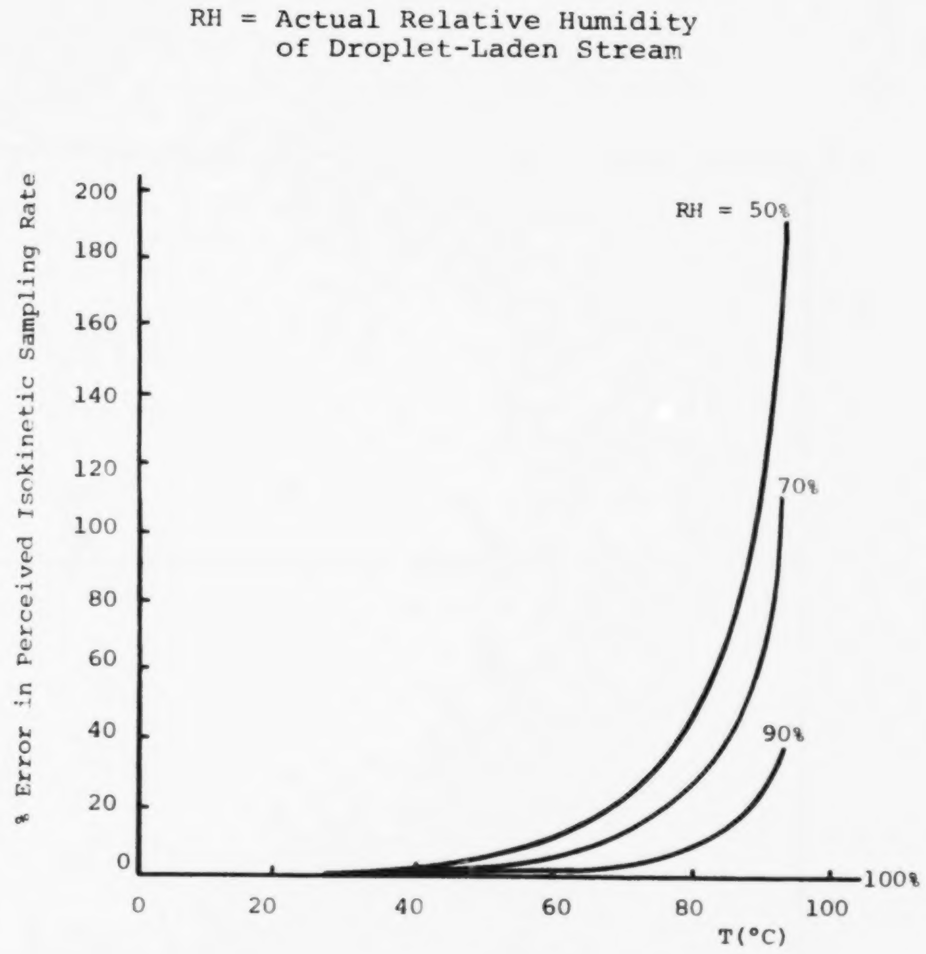


Figure 86. Ratio of measured and actual volumetric flow rate for 24-point velocity surveys with Fecheimer probe downstream of mist eliminator



RH = Actual Relative Humidity of Droplet-Laden Stream

Figure 87. Error in isokinetic sampling rate due to assumption that droplet-laden stream is saturated

Fig. 67.

Certain simplifying assumptions were made in order to arrive at some useful results. These assumptions include:

1. The radial component of the gas velocity is negligible.
2. The circumferential velocity component of a droplet at any point is the same as the circumferential velocity component of the gas.
3. The droplets are spherical.
4. The motion of an individual droplet is not affected by the presence of neighboring droplets.
5. The radial and axial components of drag force on a droplet are given by Stokes' Law.

These assumptions are similar in nature to the usual assumptions applied to the analysis of particle motion in cyclone type dust collectors (Refs. 56, 57).

Equations of motion in the radial and axial directions may then be written:

$$M_D \left(\frac{d^2r}{dt^2} - \frac{V_\theta{}^2}{r} \right) + 3\pi d_D \mu \frac{dr}{dt} = 0 \tag{1}$$

$$M_D \frac{d^2Z}{dt^2} + M_D g + 3\pi d_D \mu \left(\frac{dZ}{dt} - V_Z \right) = 0 \tag{2}$$

where M_D and d_D are the mass and diameter of a given droplet, respectively. These may be reduced to:

$$\frac{d^2r}{dt^2} + \frac{18\mu}{\rho_D d_D{}^2} \frac{dr}{dt} - \frac{V_\theta{}^2}{r} = 0 \tag{3}$$

$$\frac{d^2z}{dt^2} + \frac{18\mu}{\rho_D d_D{}^2} \left(\frac{dz}{dt} - V_Z \right) + g = 0 \tag{4}$$

where ρ_D is the liquid density and μ is the gas viscosity. Since the radial and axial accelerations are relatively small, it is convenient to simply neglect the second order derivatives in order to arrive at a system of equations which can be solved analytically. This approximation, while obviously not correct, has been shown to be of value in the analysis of cyclones (Refs. 56 and 57). For a particular form of the circumferential velocity term v_θ as used in Ref. 57, this approximation was shown to give a solution which nearly matched the solution of the actual radial equation of motion after a certain elapsed time. Again, this approximation is used routinely in cyclone analyses.

Neglecting the second order derivatives and combining equations (3) and (4) then gives:

$$\frac{dz}{dr} = \frac{18\mu}{\rho_D d_D^2}\left(\frac{r v_z}{v_\theta^2}\right) - \frac{rg}{v_\theta^2} \qquad (5)$$

Solutions to Equation (5) will then provide approximations to the trajectories of droplets entrained in the swirling flow. Simple polynomial functions were derived to approximate the velocity components of the gas, based on the measured velocity data presented in Figs. 82-85. These functions are illustrated in Fig. 88. By introducing these polynomial functions into Equation (5), the solution may be found by integration. In this manner, the trajectory of a droplet may be determined; a droplet initially located at point (r_1, z_1) moves to a point z_1) moves to a point r_2, z_2), where

(continued on page 132)

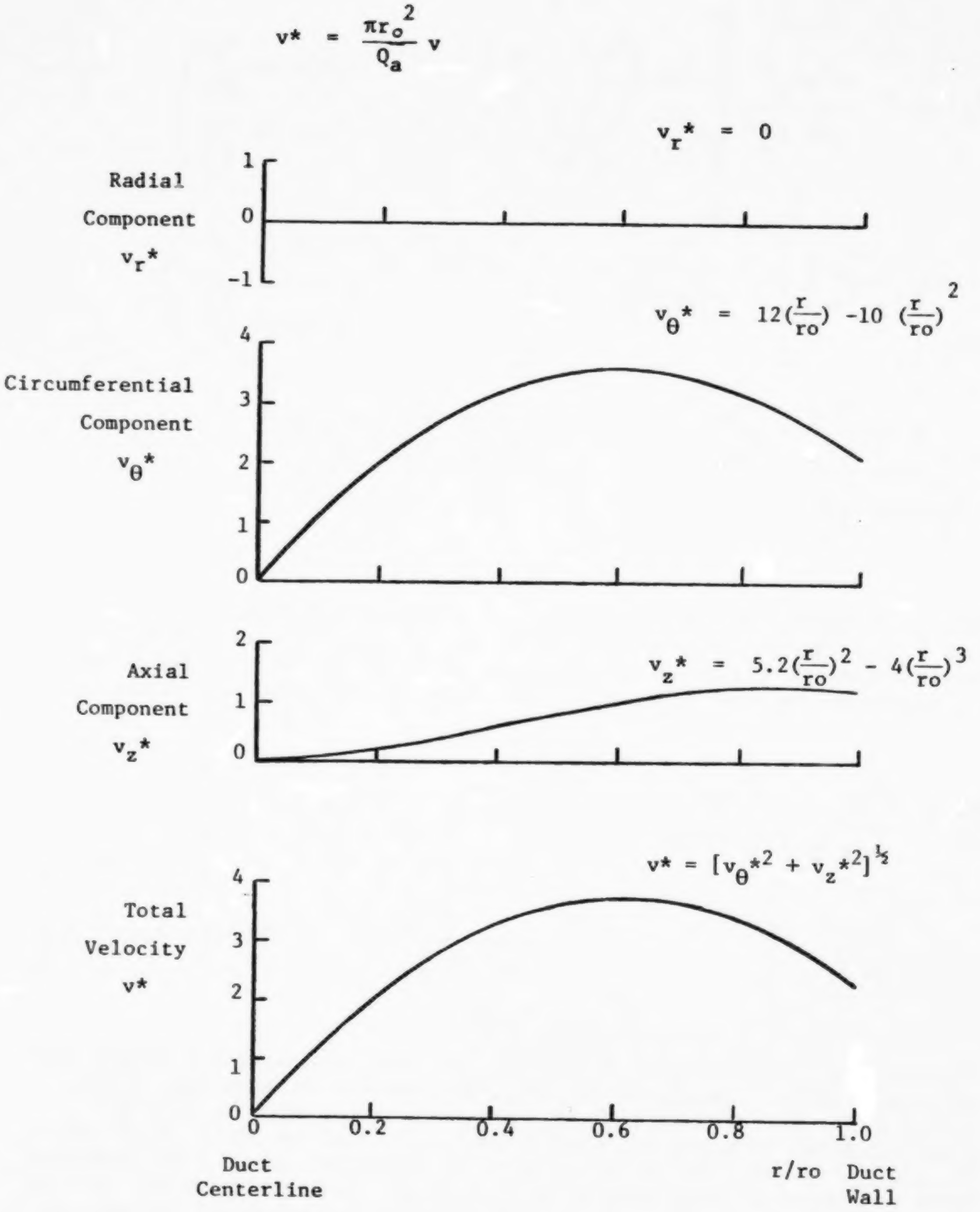


Figure 88. Approximations to velocity components measured in scrubber exhaust model

$$z_1 - z_2 = \frac{\pi^2 g r_o^6}{144\, Q_a^2}\left[\frac{100\left(\frac{r_1}{r_o} - \frac{r_2}{r_o}\right)}{\left(12-10\,\frac{r_1}{r_o}\right)\left(12-10\,\frac{r_2}{r_o}\right)} + \ln\left(\frac{12-10\,\frac{r_1}{r_o}}{12-10\,\frac{r_2}{r_o}}\right) - \ln\left(\frac{r_1/r_o}{r_2/r_o}\right)\right] + \frac{\pi\mu r_o^4}{\rho_D d_D^2 Q_a}\left[(.792)\ln\left(\frac{12-10\,\frac{r_1}{r_o}}{12-10\,\frac{r_2}{r_o}}\right) - \frac{8.64\left(\frac{r_1}{r_o} - \frac{r_2}{r_o}\right)}{\left(12-10\,\frac{r_1}{r_o}\right)\left(12-10\,\frac{r_2}{r_o}\right)} + (.72)\left(\frac{r_1}{r_o} - \frac{r_2}{r_o}\right)\right] \tag{6}$$

If r_1 is taken as the position of a given droplet at $z_1 = 0$ and r_2 is the radius of the duct ($r_2 = r_o$), the distance downstream of the mist eliminator ($z = 0$) at which the droplet is impacted on the duct wall (in duct diameters) is given by:

$$\frac{z_{imp}}{2r_o} = \frac{\pi^2 g r_o^5}{288\, Q_a^2}\left[\frac{50\,(r_1/r_o - 1)}{12-10\, r_1/r_o} + \ln\left(6r_o/r_1 - 5\right)\right] + \frac{\pi\mu r_o^3}{2\rho_D d_D^2 Q_a}\left[.72\left(\frac{r_1}{r_o} - 1\right) - \frac{4.32\left(\frac{r_1}{r_o} - 1\right)}{12-10\,\frac{r_1}{r_o}} + (.792)\ln(6-5r_1/r_o)\right] \tag{7}$$

This impaction distance is shown for various droplet sizes and initial radial positions in Fig. 89, based on average conditions from the cyclonic flow velocity tests and an assumed droplet mass density of 1000 kg/m^3. As can be seen from Fig. 89, all droplets 30 μm or larger in diameter should be removed from the flow before reaching the first test port level in the cyclonic flow model. Some droplets on the order of 10 μm and smaller, however, should remain entrained in the gas stream throughout the entire test section of the cyclonic flow model.

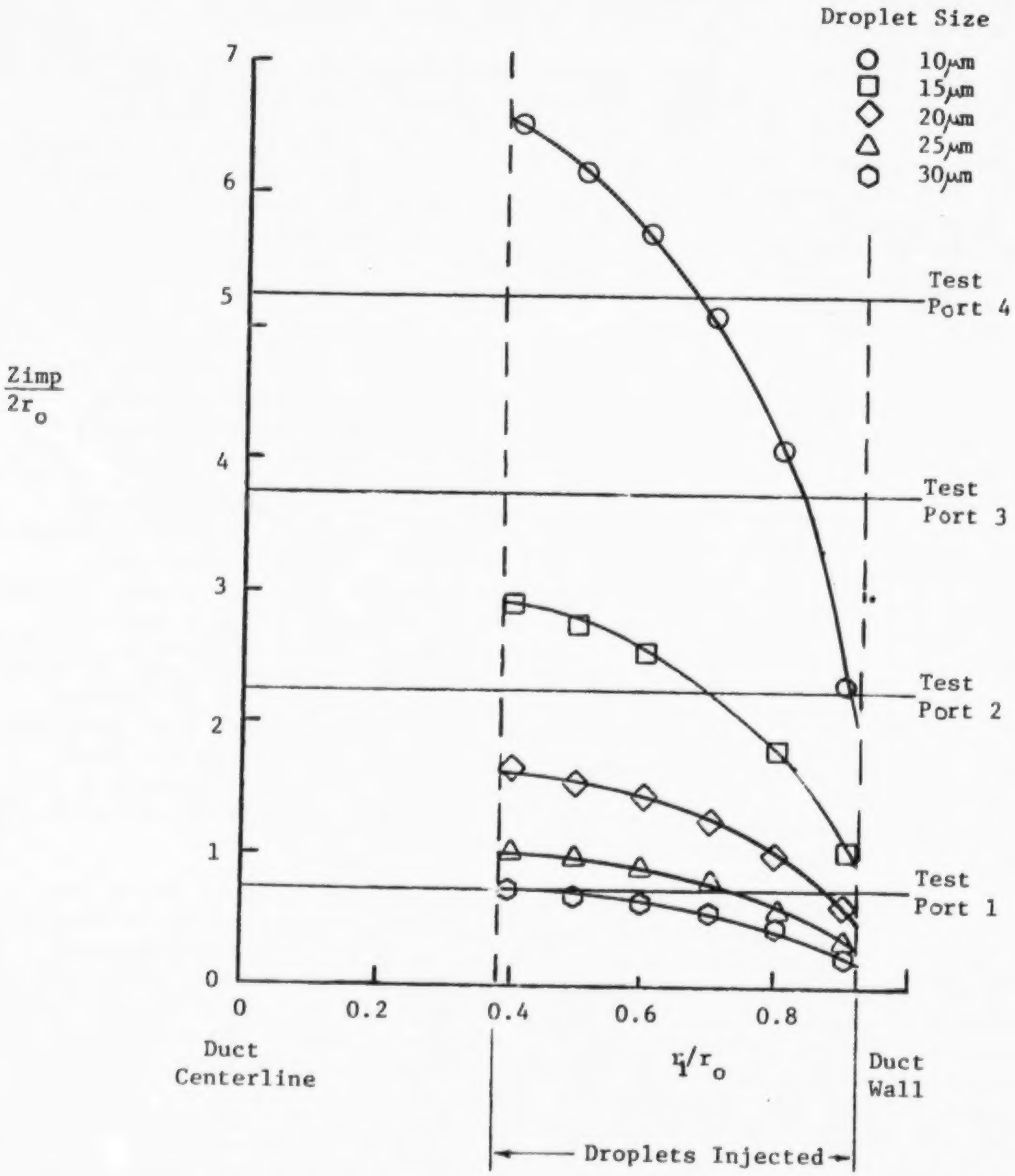


Figure 89. Number of duct diameters downstream of mist eliminator where water droplets are impacted on duct wall, scrubber exhaust model

Trajectories of 10 μm droplets as given by Equation (6) are plotted in Fig. 90. These results show that the central area of the duct should have no liquid droplets, and that the concentration of droplets near the duct walls should increase continually with distance downstream of the mist eliminator, less those droplets actually deposited on the walls.

The results of this approximate analysis agree qualitatively with the observations made at the Seneca Treatment plant. In addition, measurements of droplet size made by another investigator at the Seneca Treatment Plant at location B in Fig. 62 were reported to indicate a mass median diameter of approximately 5 μm (Ref. 58) in close agreement with the results of the analysis. The predicted behavior of liquid droplets in cyclonic flow again points to the need to be able to account for the mass of liquid in droplet form at various points in the flow stream.

Liquid Droplet Testing--

A sampling method was selected for evaluation in the scrubber exhaust model on the basis of the information gained through the methodology review and the preliminary field test program. The method involves collecting two gas samples with a heated probe in order to vaporize all the collected liquid. The sampled liquid in droplets, as well as the liquid present in vapor form at the sample point, is then collected in a condenser apparatus after passing through a particulate filter. The first sample is collected isokinetically with a standard sampling nozzle directed into the gas stream. Moisture collected in this first gas sample will consist of the liquid in both vapor and droplet form. The second gas sample is collected with a sampling nozzle which inertially separates the droplets from the collected gas sample. Moisture collected in this sample should consist of only the vapor phase. Comparing the collected moisture in the two gas samples then will provide the mass of liquid in droplet form.

This method was chosen in view of the difficulties reportedly encountered with other possible droplet collection schemes. Precutters, such as that used in the preliminary field tests, allow collected water to be reevaporated by the sample stream. This difficulty also exists when filters are used to remove droplets from a sample stream. The various problems associated with humidity measurements in a droplet-laden stream are discussed in Ref. 59, which also recommends the use of an inertial separation type probe. These difficulties were also confirmed by experiments in the scrubber exhaust model with entrained liquid droplets in which various types of hygrometers and dew point indicators were used with and without filters in attempting to measure the humidity of the gas stream. Repeatable results could not be achieved, and these methods were abandoned.

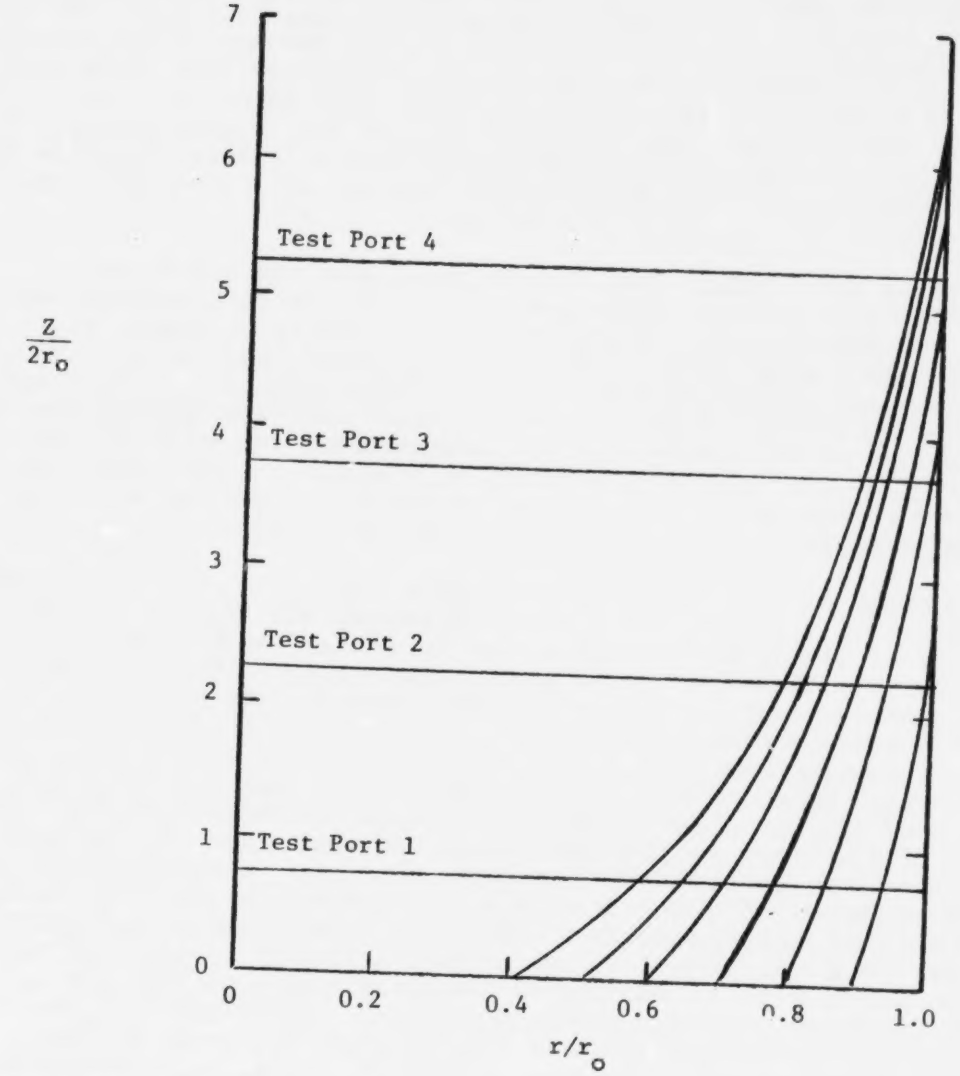
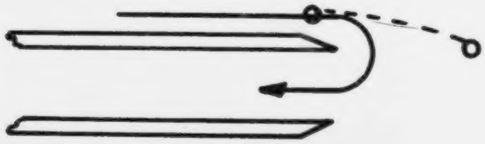


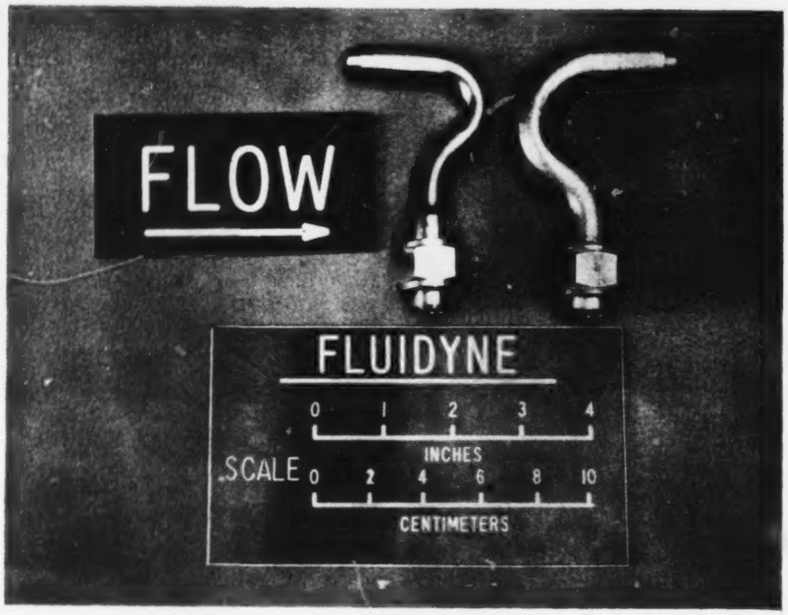
Figure 90. Trajectories of 10 μm water droplets in scrubber exhaust model

Several nozzles designed to remove liquid droplets are shown in Figs. 91-95, together with a standard sample nozzle to be used for isokinetic sampling. The simplest concept for inertial separation is illustrated by Fig. 91, in which a standard sampling nozzle is simply oriented in a downstream direction and a sample is collected at a low flow rate. Figure 92 illustrates a modification to this concept in which a shield is added to the downstream-facing standard nozzle to inhibit growth of a liquid film on the probe surface and to impart a radially outward motion to the droplets. A suction slot, through which the liquid film is drawn off, and a separate sampling area are employed in the nozzles shown in Figs. 93 and 94. A similar concept was followed in the design of the nozzle illustrated in Fig. 95, but this nozzle faces in the direction of the flow in order to avoid potential disturbances from locating the sampling slot in the wake of the sample probe. The sample is collected through a slot which forces the flow to pass around a sharp obtuse angle in the probes shown in Figs. 94 and 95.

It was originally intended to evaluate the two-sample method in the cyclonic flow downstream of the mist eliminator in the scrubber exhaust model. However, after a number of initial tests were made in the cyclonic flow test section this test plan was abandoned because of difficulties in accounting for the total mass of water removal from the flow stream due to impingement on the turning elbow upstream of the mist eliminator and on the face of the mist eliminator itself (see Fig. 67). This made evaluation of the performance of the nozzles with an acceptable degree of accuracy impossible.

Testing of the various two-sample nozzle arrangements was then moved to a position in the horizontal air supply ductwork upstream of the mist eliminator as indicated in Fig. 67. Although this point is not a sufficient number of duct diameters upstream of the elbow as specified by EPA Method 1, this site was selected to ensure that the injected droplets were sufficiently well-mixed in the flow and that a steady state liquid-vapor mixture was reached before the test point. Samples of the droplet-laden stream were collected at the center of the duct at the test location with each of the proposed inertial droplet separator nozzles and passed through a heated probe which evaporated any collected liquid. The moisture ratio of this extracted sample as determined by collection of water in a condenser following EPA Method 5 procedures was then compared with an estimated humidity ratio of the gas stream based on the rate of injected water droplets and the thermodynamic state of the air in the duct upstream of the water injection point. An evaluation of the effectiveness of the proposed nozzles in removing droplets from the stream could then be made on the basis of this comparison.




FLOW
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0 1 2 3 4
INCHES
0 2 4 6 8 10
CENTIMETERS

Figure 91. Standard sampling nozzle for use as inertial droplet eliminator nozzle in two-sample method

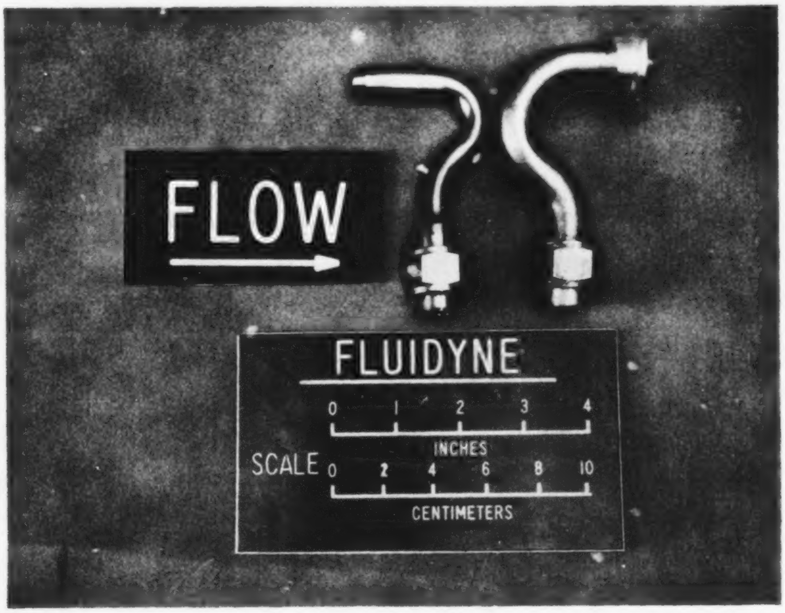
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Figure 92. Standard nozzle with shield for use as inertial droplet eliminator nozzle in two-sample method

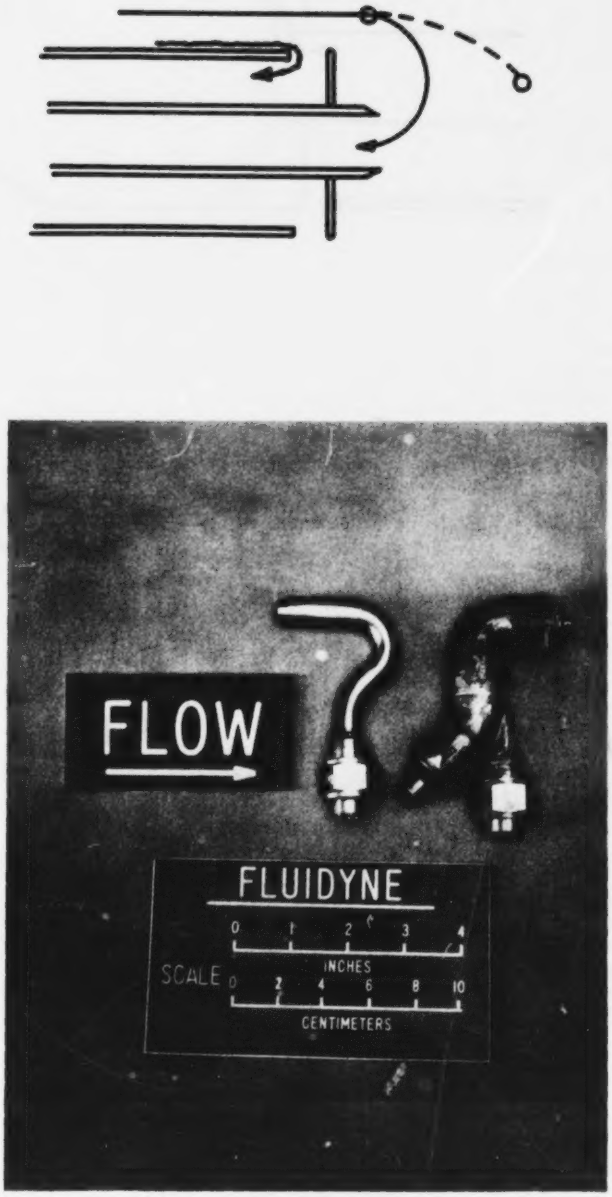
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Figure 93. Inertial droplet eliminator nozzle with suction slot for liquid film removal

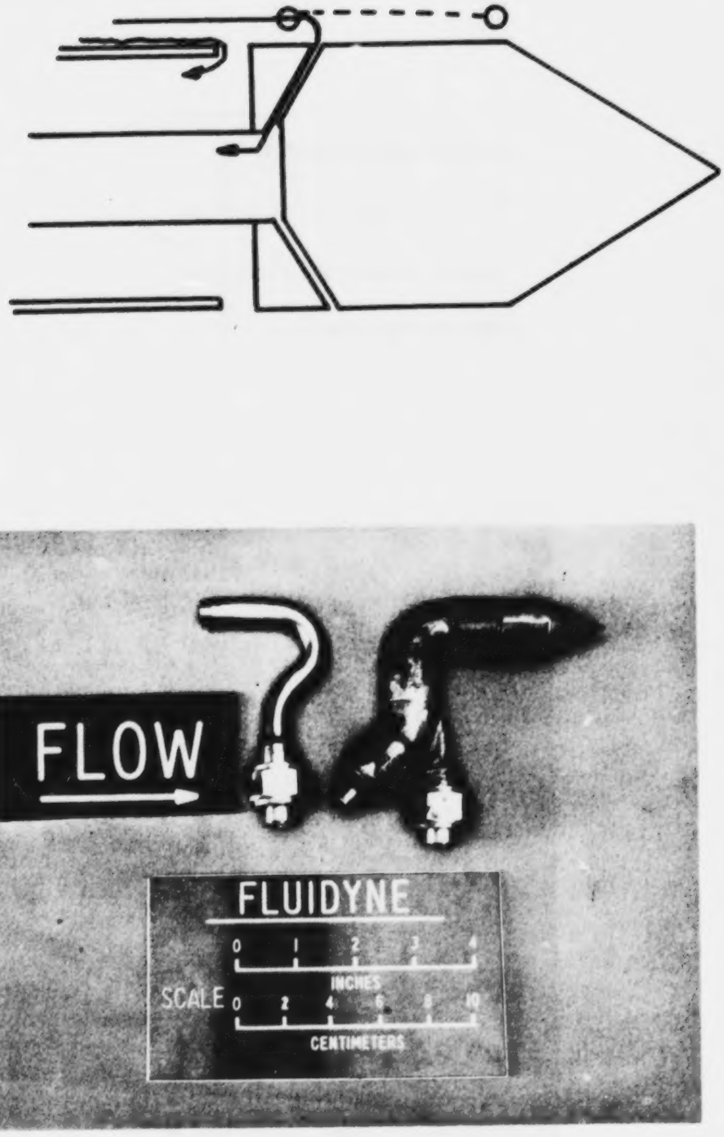
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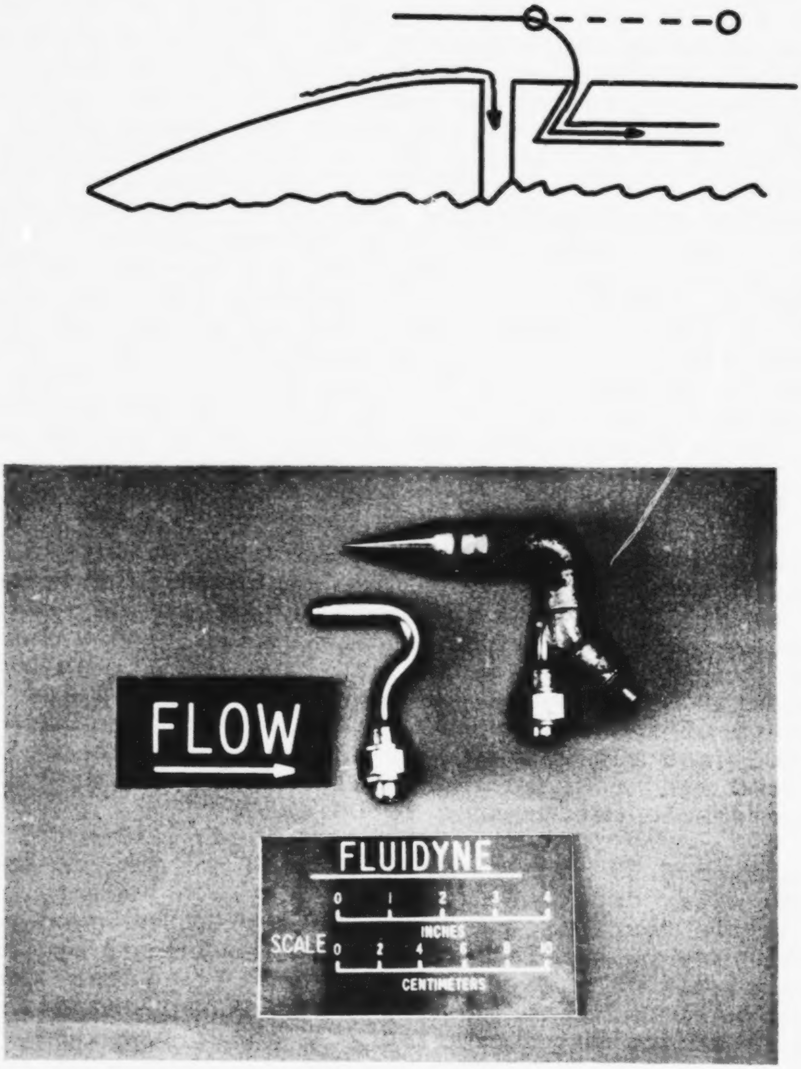
Figure 94. Inertial droplet eliminator nozzle with suction slot and aerodynamic tail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CENTIMETERS

Figure 95. Inertial droplet eliminator nozzle with suction slot oriented in upstream direction

A total of 64 such screening tests were made with various proposed inertial droplet separator nozzles. The results of these tests showed that the separator nozzle illustrated in Fig. 95 had the greatest potential for use in the two-sample method. The standard sampling nozzle oriented in a downstream direction (Fig. 91), even when used with a liquid film shield such as shown in Fig. 92, or with other more aerodynamically designed shields and droplet deflectors not pictured here, consistently indicated humidity ratios far in excess of the estimated duct humidity. In certain tests the indicated humidity ratio actually exceeded that possible by collecting all of the droplets passing the sample point. This poor performance was attributed to the presence of liquid film collecting on the surface of the nozzles and to large droplets which collected on the portions of the nozzle upstream of the sample point and on the heated probe (Figs. 96 and 97). These droplets were periodically sheared from the surfaces on which they collected into the flow stream and conceivably could have been collected by the nozzle. The performance of the nozzles shown in Figs. 93 and 94 was somewhat better in general, due to the use of the suction slot to remove liquid film buildup, but was found to be very erratic. This is very likely due to the droplet shearing problem described above, which is inherently present when the sampling point is downstream of other surfaces on which droplets can collect (see Fig. 98). This problem is avoided by the design of the nozzle illustrated in Fig. 95 as can be seen in Fig.100. This nozzle indicated the best performance in the screening tests.

A careful evaluation of the two-sample method was then made on the basis of these screening tests using a standard nozzle to sample the liquid droplets and vapor and the inertial droplet separator nozzle shown in Fig. 95 to sample for vapor content only. The elbow was removed from the air supply ductwork in order to eliminate any flow disturbances. The thermodynamic state of the air ahead of the droplet injection point was measured, and all water deposited on the walls of the duct was collected and measured. This allowed an accurate assessment of the nozzle performance to be made.

A standard 6.35 mm (1/4 in) sampling nozzle was used to collect the water droplets isokinetically. A summary of the standard nozzle tests is shown in Table 13. The good agreement between the mass concentration of water collected by the nozzle when compared with the water injected and the water collected on the duct wall indicates that the standard isokinetic sampling technique is sufficient to collect the water droplets.

The results of the tests with the inertial droplet separator nozzle are shown in Table 14. The "actual duct humidity" shown in Table 14 is determined from a computer model of the evaporation of the water droplets. This model used a finite

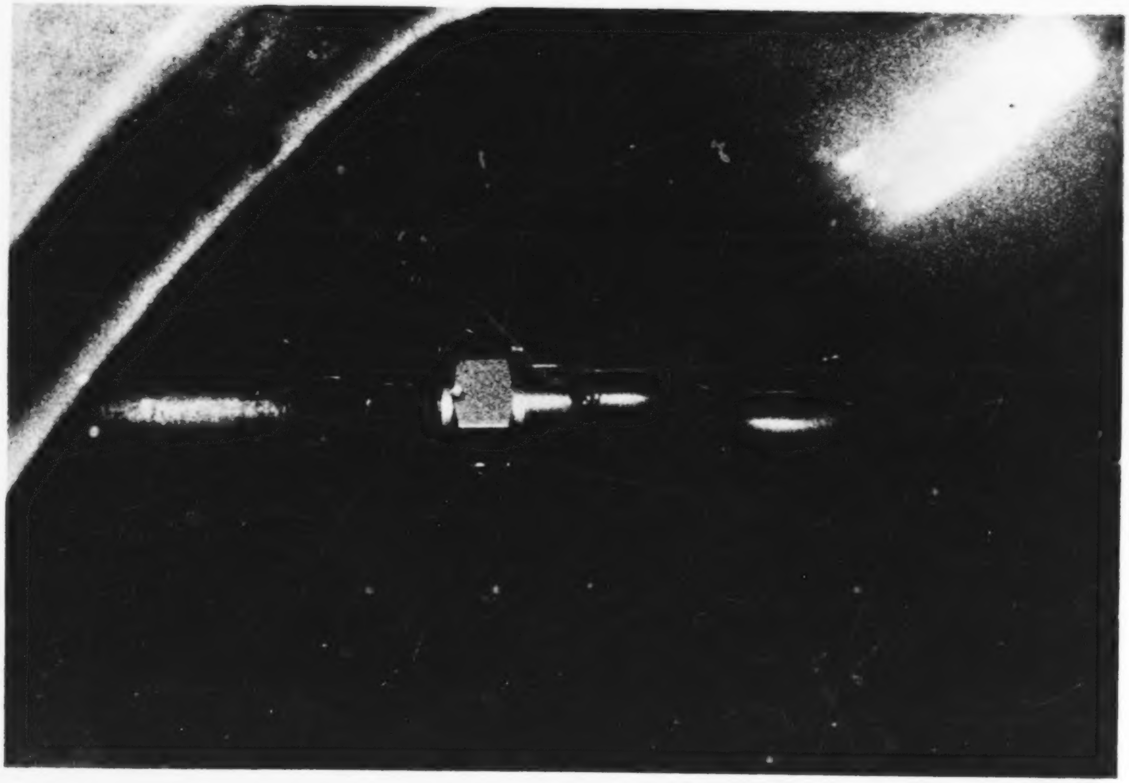

Figure 96. Standard sample probe collecting isokinetic sample in scrubber exhaust model

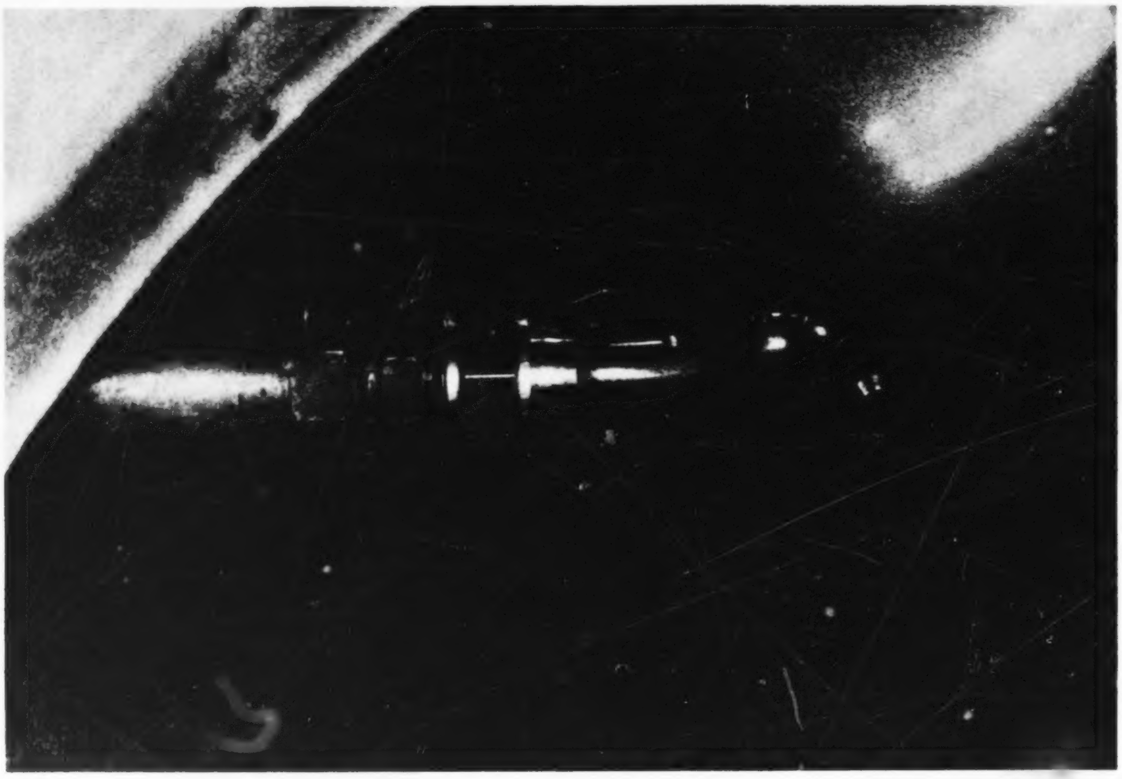

Figure 97. Standard sample nozzle oriented in downstream direction as inertial droplet separator in scrubber exhaust model

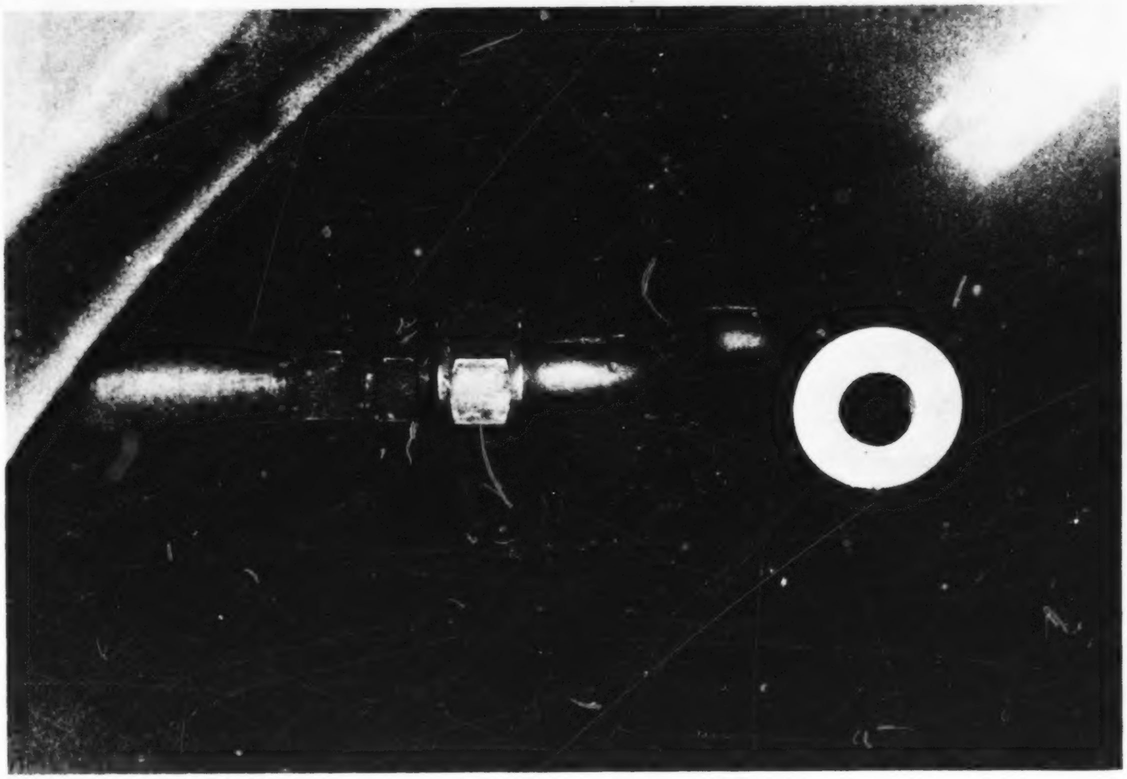

Figure 98. Standard sample nozzle with droplet shield as inertial droplet separator in scrubber exhaust model

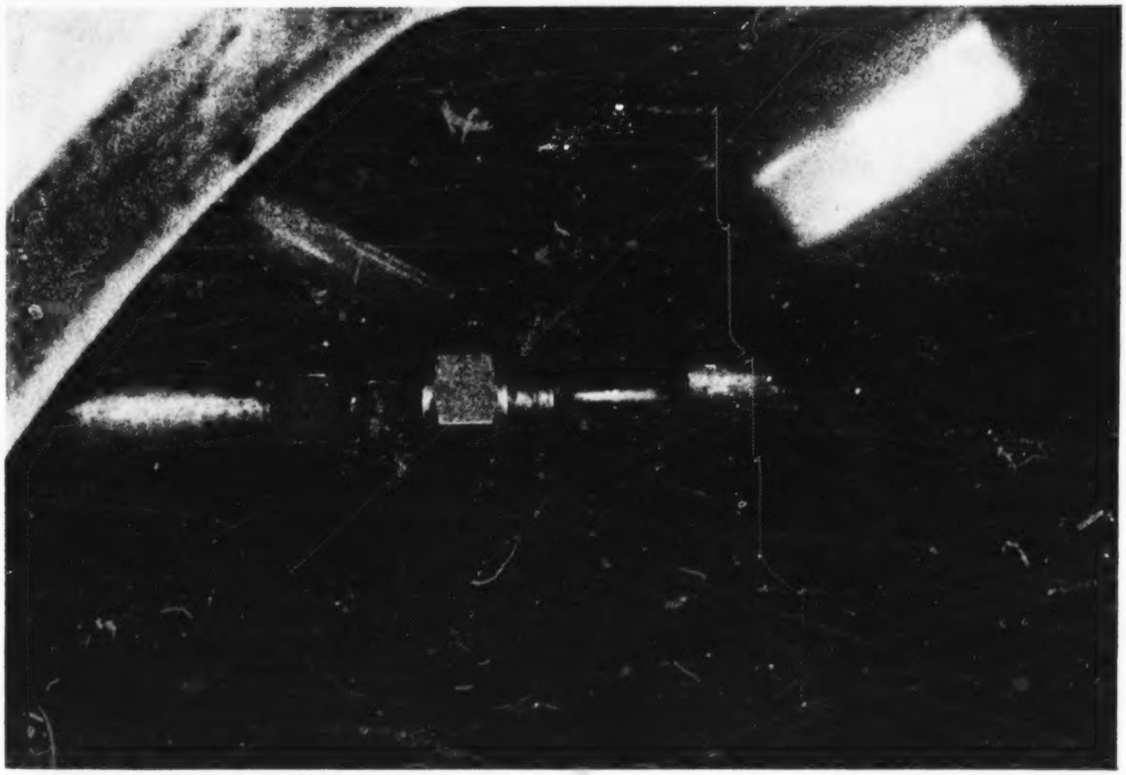

Figure 99. Inertial droplet separator nozzle shown in Figure 94 in scrubber exhaust model

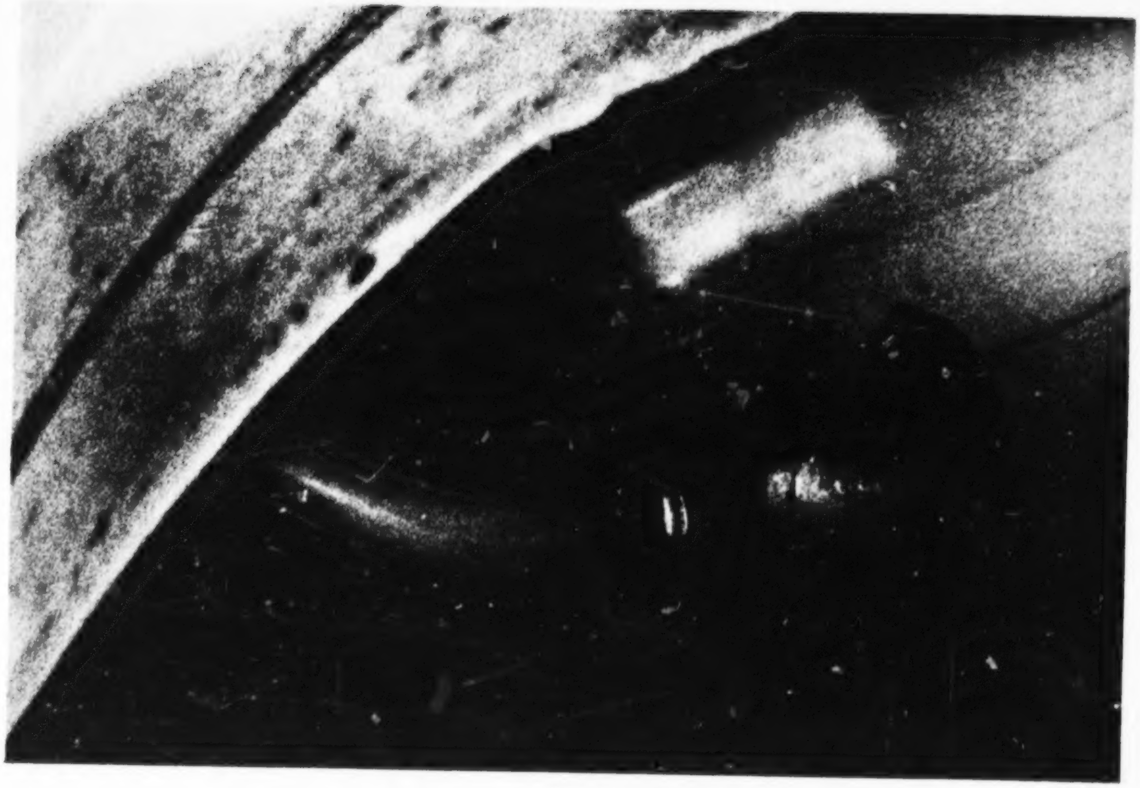

Figure 100. Inertial droplet separator nozzle shown in Figure 95 in scrubber exhaust model

TABLE 13. COMPARISON OF MEASURED MASS FLOW RATE OF WATER VAPOR AND DROPLETS WITH ACTUAL MASS FLOW RATE

	Measured			Actual				
Run No.	$W_{meas.}$ $\frac{gm_{water}}{kg_{air}}$	$\dot{m}_{air}$ (kg/hr)	$\dot{m}_{water}$ (kg/hr)	Ambient Water Vapor in Air (kg/hr)	Injected Droplets (kg/hr)	Deposited On Wall (kg/hr)	$\dot{m}_{water}$ (kg/hr)	$\frac{\text{measured}}{\text{actual}}$
106	16.36	4893	80.10	23.19	75.71	21.39	77.51	1.03
107	16.50	4867	80.31	23.12	75.71	20.35	78.48	1.02
108	16.27	4840	78.75	22.51	75.71	23.19	75.03	1.05
109	16.48	4874	80.32	24.42	75.71	24.13	76.00	1.06
110	16.72	4867	81.38	24.38	75.71	24.37	75.72	1.07

W_{meas} = Concentration of water in collected sample

$\dot{m}_{air}$ = Flow rate of air in model

$\dot{m}_{water} = W_{meas} \ \dot{m}_{air}$

$\dot{m}_{water}$ = Ambient vapor entering model + injected droplets - water deposited on duct wall

TABLE 14. PERFORMANCE OF INERTIAL DROPLET SEPARATOR NOZZLE

Run No.	$W_{measured}$* $\frac{gm_{water}}{kg_{air}}$	W_{actual}** $\frac{gm_{water}}{kg_{air}}$	1 Mass of Droplets at Sample Point $\frac{gm_{water}}{kg_{air}}$	2 Mass of Droplets Removed by Nozzle $\frac{gm_{water}}{kg_{air}}$	Nozzle Efficiency $\eta = \frac{1}{2}$
111	9.31	8.25	7.39	6.31	.85
112	9.91	8.17	7.57	5.82	.77
114	10.72	8.68	8.40	6.35	.76
115	12.28	8.28	10.17	6.15	.60
116	13.02	8.78	9.54	5.28	.55
					Avg. = .71

* Concentration of water vapor indicated by collected sample

** Concentration of water vapor calculated with computer model element method to analyze the evaporation of individual droplets of diameter d_D by the equation

$$\dot{m}_E\ (d_D) = \frac{12\ D_v \rho_a}{{d_D}^2 \rho_w}\ m\ (d_D) \left[0.622\left(\frac{p_v}{p-p_v}\right) - w_d\right] \qquad (8)$$

where $\dot{m}_E\ (d_D)$ = mass rate of evaporation of droplets of size d_D

D_v = binary vapor diffusivity

ρ_a = mass density of dry air

ρ_w = mass density of water

p = static pressure in duct

p_v = vapor pressure of water at droplet surface temperature

w_d = average humidity ratio in duct

$m(d_D)$ = mass of droplets in a computational bandwidth characterized by diameter d_D

A droplet size distribution at the spray nozzle injection point was determined from manufacturer's information (Fig. 101). Deposition of droplets on the duct wall was also computed by the model following methods presented in Refs. 60 and 61 and was found to agree well with the water collected on the duct walls in the evaluation tests.

The results shown in Table 14 indicate that the inertial droplet separator nozzle removed roughly 70% of the droplets existing at the sample point. Therefore, this nozzle could be used to determine the humidity of the droplet-laden stream by using a calibration factor as determined by the evaluation tests. The removal efficiency of the droplet separator is very likely dependent on the size distribution of the droplets, however, and further evaluation of the separator with different sized droplets would be desirable.

EVALUATION OF SAMPLING TECHNIQUE

The basic sampling technique developed for wet scrubber

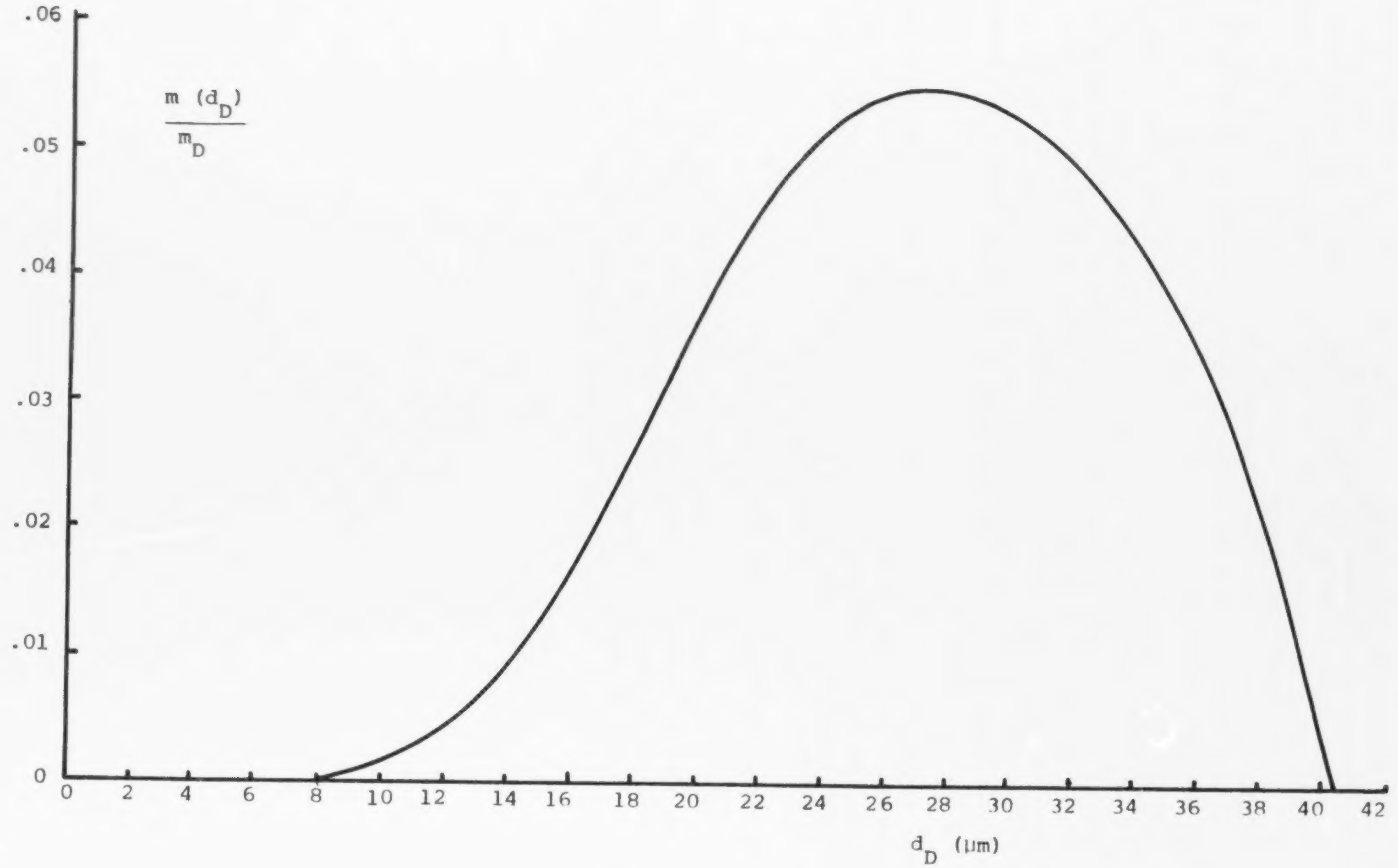

Figure 101. Droplet size distribution at spray injection point

particulate emission sampling involves the use of a Fechiemer probe for use in volumetric flow measurement and to determine proper angular positioning for the sample probe, an inertial droplet separator nozzle for use in humidity measurement, and a Method 5 type sampling probe to collect the particulate. Based on the information obtained in the model studies program, this approach should provide satisfactory emission measurements in a typical wet scrubber exhaust.

Further development and evaluation of the inertial droplet separator nozzle is desirable. If such a nozzle could be developed to eliminate all of the droplets at a given sample point, then the use of a heated probe and condenser in conjunction with the droplet eliminator would be unnecessary. In such a case, the sampled gas could simply be analyzed for moisture content with any of various available types of humidity measurement devices.

The question of the required number of sample points was not addressed in this study. Since the basic particulate concentration measurement follows EPA Method 5, the required number of sampling points for this method is recommended for use in scrubber exhaust measurements.

APPLICABILITY TO OTHER EMISSION SOURCES

The particulate sampling method developed for wet scrubbers should be generally applicable to any confined stream with entrained liquid droplets. The Fecheimer probe is not required, of course, unless cyclonic flow is present. This probe also should not be used if multiple vortex cyclonic flow is present (see Ref. 2).

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APPENDIX

VELOCITY INSTRUMENTATION FOR LOW VELOCITY, PARTIALLY CONFINED SOURCE PARTICULATE SAMPLING

By

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INTRODUCTION

Procedures and instrumentation for the determination of velocity and particulate concentration have been established and studied for emission sources having well-defined flow fields and velocities above 1.5 to 2 m/sec (Ref. A1). Little information is available, however, concerning procedures and instrumentation applicable to emission sources for which the flow is not well defined or the effluent stream is not confined. An example of such an emission source is the roof monitor or roof ridge ventilator. This type of emission source is characterized by low velocities and complex, often circulatory, flow fields.

Knowledge of the velocity of an emission stream is necessary for determination of the volumetric flow rate, which must be known in order to establish the total particulate emission level. A further requirement for establishing the velocity is dictated by the need to establish isokinetic sampling rates, although this is typically not of great importance in the study of roof ventilators due to the small size of particulate generally emitted by such sources.

Measurement of the velocity and determination of the volumetric flow rate are complicated by low velocities and circulatory flow, as opposed to the situation existing in power plant ducting and exhaust stacks, for example. In such a situation, it has been shown (Ref. A2) that a small number of measurements with an S-tube over the cross section of a duct or stack can often provide an accurate determination of the volumetric flow rate. At low velocities (approximately 1 m/sec or less), however, the S-tube or pitot static tube introduce a high degree of uncertainty to velocity measurements due to the extremely small magnitude of the dynamic pressure of the gas stream. In addition, the possibility of regions of reverse flow and large degrees of nonuniform flow angularity in unconfined source emissions requires the determination of the flow direction as well as velocity magnitude in order to establish the net volumetric flow rate.

Thus, the selection of suitable velocity instrumentation for use in connection with low velocity, unconfined sources is an important consideration. Therefore, the suitability of a number of velocity instruments was evaluated for this purpose.

TYPES OF VELOCITY INSTRUMENTS

Several types of velocity measuring instruments are listed in Table A1 along with some brief comments concerning the characteristics of each type. There are generally several manufacturers for each type of instrument, but those listed in Table A1 provide a representative sample. A brief description of the principle of operation and an evaluation of the possible usefulness of each type of instrument is included in the following.

Pitot Static Tubes or S-tubes

The principle of the pitot static tube or S-tube is to measure, by means of a probe inserted in the flow, the difference between total pressure and static pressure (or nearly static pressure, in the case of the S-tube). Thus, the dynamic pressure (or a quantity proportional to the dynamic pressure) is obtained directly from the measurement, and the velocity may be computed if the fluid density is known. This type of instrument is widely used for velocity measurement, and the S-tube is the standard EPA-approved instrument for sampling in ducts and stacks. However, since the dynamic pressure is extremely small in low velocity gas flows, accuracy of measurements becomes poor. In addition, determination of flow direction is not a suitable application for a standard pitot static tube or an S-tube.

The useful velocity range of the S-tube can be extended to some extent with the use of a purge gas flow through the S-tube and a fluidic amplifier. The principle of such an instrument involves a pneumatic bridge between the two S-tube lines, which is balanced in the no-flow condition. As a pressure differential develops between the two S-tube ports, a secondary flow of purge gas is induced in the pneumatic bridge which is proportional to the fluid velocity. This arrangement extends the low velocity range of the S-tube to approximately 15 m/min and prevents fouling of the tube in a particulate stream, since no fluid actually enters the S-tube. However, the accuracy of this instrument is poor in the very low velocity range.

TABLE A1. LOW VELOCITY INSTRUMENTATION

1m = .3048 ft.
°C = 5/9 (°F -32)

INSTRUMENT	VELOCITY RANGE (ft/min)	MAX.OPER. TEMP. (°F)	FUNCTIONING IN PARTICULATE STREAM	ACCURACY AT 1 ft/sec	DIRECTIONAL SENSITIVITY	RUGGED-NESS	TYPICAL INSTRUMENT MANUFACTURER	TYPICAL INSTRUMENT MODEL	APPROX. COST	COMMENTS
Pitot Tubes or S-Tubes										
1.with Inclined Manometer	600+	800+	Only limited by probe blockage	N/A	Yes (S-tube)	Good	Dwyer		$100	
2.with Micromanometer	400+	800+		N/A		Good	Dwyer		$200	Affected by Vibration
3.S-tube with purge flow	50-1500	800+	Good	±50%	Poor	Good	Hastings-Raydist	GSM-ID5K	$1900	Good for uniform flow; auxiliary readout needed below ~ 100 ft/min
Vane or Propeller Anemometers										
4.Vane Anemometer	50-5000	250	Fair	±20% (est)	No	Fair-Good	Flowrite	MRF	$100	Direct Velocity indication
5.Rotating Vane (mech)	30-5000	250	Fair	±20% (est)	± in direction of alignment	Fair-Good	Davis		$200	Cumulative reading
6.Rotating Vane (elect)	25-5000	250	Fair	±20% (est)		Fair-Good	Davis, Gill		$800	Continuous reading
7.Propeller Vane	25-5000	220	Fair	±20% (est)	Yes	Fair-Good	Gill		$500	
8.Propeller with purge gas cleaning	25-5000	220	Good	±20% (est)			Gill		$200 +purge gas system	
Heated Element Anemometers										
9.Hot Wire	10-6000	800	Needs occasional Cleaning	±20%	No	Poor	Thermo-Systems	1610	$1000	Temp. range may vary
10.Hot Film	10-6000	300	Needs occasional Cleaning	±20%	to 0° or 180°	Fair	Thermo-Systems	1650	$500	Response time may be too fast
11.Wedge hot film		500	Needs occasional Cleaning		No	Fair	Thermo-Systems	1234H	$1300 w/readout	Not temp. comp. (+ $100 for temp. comp model.)
12.Hot thermopile	10-3000	200	Needs occasional Cleaning	±6%	to 0° or 180°	Good	Hastings-Raydist	PCI-30	$700	Good field instrument.
Fluidic Anemometers										
13.Parallel Jet	30-8000		Tested to 25 g/m³		Possible	Good	Bowles		$200	
14.Perpendicular Jet	12-3000	400	4.5 g/m³		Possible	Good	FluiDynamic		$1000	Temp. range may vary
15.Heated tube-purge flow cooled	60-6000		Good	±50%	Possible	Good	Hastings-Raydist	API-6K	$1500	
16.Vortex Shedding Anemometer	100+			N/A	No	Good	J-Tec		$1000	Under Development
17.Ion Deflection	1-12,000	140	Needs some Cleaning	±4%	Yes	Good	Thermo-Systems		$2000	
18.Sonic Pulse	20-2000	120	Relatively Unaffected	±30%	Yes	Poor	E.G.&G.		$7000	Under Development
19.Laser Doppler	.03-2x10⁵	Unlimited	Good for Small Particulate		Yes	Poor	Brown-Boveri, DISA		$10K - 20K	Not a field instrument at this time.

Vane or Propeller Anemometers

A vane or propeller anemometer is positioned normal to the flow velocity. The flow through the anemometer imparts aerodynamic force to the vanes, or propeller, which then rotate at a rate proportional to the fluid velocity. In a mechanical anemometer, the rotation of the instrument is recorded on a dial as a cumulative linear distance, which provides the fluid velocity when divided by the measurement time, or as a direct velocity indication. Electronic instruments provide a continuous signal which can be recorded. The signal polarity can be proportional to the flow direction. A direct velocity indicating vane anemometer does not respond correctly to a reversed flow. A rotating vane anemometer with a cumulative distance indication allows the determination of a net velocity over the measurement time since a reversed flow will cause distance to be subtracted from the cumulative total. When the indicated cumulative distance is then divided by the measurement time, the resulting velocity is the net velocity which has passed through the anemometer. A propeller vane anemometer aligns itself with the flow, thus providing an indication of flow direction as well as velocity.

These instruments allow measurement of lower velocities than do pitot static or S-tubes. However, the rate of rotation is influenced by bearing friction; thus, this type of instrument must be calibrated frequently with wear, and the calibration may be affected by particulate matter. The use of a purge gas flow to clean the bearings is a common means to prevent fouling of the instrument in a particulate stream. In addition, calibrations are nonlinear near zero velocity, causing poor accuracy at velocities near the stated minimum (approximately 7.5-15 m/min) for this type of instrument.

Heated Element Anemometers

The principle of operation of hot wire and hot film anemometers is essentially the same. The sensing element (usually platinum wire or film) is heated, either with a constant electric current or to a constant temperature. When the element is introduced in a fluid stream, the heat transfer from the element is proportional to the fluid velocity. The output from these instruments is then either the resistance of the element, with constant current, or the electric current necessary to maintain the heated element at constant temperature, which is proportional to the fluid velocity. Commercially available instruments generally incorporate temperature compensation, so that calibrations are not affected by fluid temperature. Since the heat transfer from the sensing element will change with a significant buildup of particulate matter, this type of instrument will need occasional cleaning for use in a particulate-laden stream, although the hot film type is less susceptible to fouling. Frequent calibration is also advisable.

A heated thermocouple (or thermopile) anemometer also provides output due to the heat transfer from heated elements in a flowing stream. In this type of instrument, the sensing elements are hot junctions of a thermopile, while alternate junctions are not heated to provide for temperature compensation. The reduced thermocouple current when the hot junctions are cooled by a flowing gas stream is proportional to the velocity. As in the case of hot wire or hot film anemometers, occasional cleaning is necessary in a particulate stream.

Directional sensitivity is not a basic feature of heated element anemometers. However, protective caps designed for some instruments of this type provide the additional capability to determine yaw angle in a flow.

Fluidic Anemometers

One type of fluidic velocity measurement instrument incorporates a jet of fluid, compatible with the fluid whose velocity is being measured, which is introduced into the flow, either parallel or perpendicular to the stream. This fluid jet impinges on two sensing ports situated such that the pressure at these two ports is equal for no flow. When introduced into a flowing stream the jet is deflected, causing a pressure differential between the two sensing ports. This differential pressure is the output of the sensor and can be made linear with the velocity depending on the supply pressure for the jet. The parallel jet type sensor requires lower supply pressures than the perpendicular jet type (Ref. A3). The operational principle does not preclude use in moderate particulate concentrations as long as the tubing systems do not become blocked. Two or three sensors could be arranged to determine orthogonal velocity components. If positive and negative pressures can be distinguished, reverse flow should also be detectable with fluidic sensors.

Another type of velocity measurement instrument which employs fluidic principles involves a tube through which purge gas is continually injected into the flow. A pressure differential caused by the flow at two purge gas outlets induces a secondary flow of purge gas through a heated tube inside the instrument. This secondary flow cools the heated tubing and an electrical output results following the same principle as a heated element anemometer. Since the cooling flow is clean purge gas and not the actual flow being measured, this type of instrument would function well regardless of particulate concentration. However, the output is very nonlinear and the minimum velocity is about 0.3 m/sec.

Vortex Shedding Anemometer

A new velocity measurement instrument under development employs vortices generated by a strut and counted by an ultrasonic sensor (Ref. A4). The frequency of vortex generation is directly proportional to the velocity if the Strouhal number of the obstruction is known, thus providing a calibration. The instrument reportedly has great accuracy at velocities as low as 0.5 m/sec, and based on the assumption of a constant Strouhal number over a wide Reynold's number range, should be insensitive to variations in fluid density, temperature and pressure. However, the characteristics of the instrument have not been sufficiently established to make a judgment as to its applicability in particulate streams. A concept for development of a direction-sensitive instrument employing this concept has also been reported (Ref. A4).

Ion Deflection Anemometer

This type of instrument utilizes an ion-emitting source in a tube aligned parallel to the flow. The ions are projected radially from the source toward the walls of the tube. A flow through the tube then causes a deflection of the ion stream which is directly proportional to the total mass flow through the tube, from which the velocity is deduced. Flow direction through the tube is also indicated by this type of instrument making it useful in reversed flow situations. The presence of particulate matter in a flow, however, may cause the velocity calibration to be in error. In addition, the tube would require occasional cleaning, since buildup of particulate could interfere with the ion stream and collector.

Sonic Pulse and Laser Doppler Instruments

The sonic pulse type instrument employs the difference in time for oppositely-directed sound waves to travel a fixed distance to deduce the flow velocity. Two-or three-axis systems allow the measurement of velocity components, giving the information needed for volumetric flow evaluation even in highly turbulent flows. Particulate matter should have little effect on such an instrument. The laser Doppler type instrument determines the shift in frequency caused by scattering of a light from a monochromatic source (laser). The scattering is accomplished by particles introduced in the flow, assumed to move with the velocity of the fluid; thus, the velocity associated with the measured Doppler shift is the velocity of the fluid. In a flow containing various sized particulates, some of which do not move with the fluid velocity, the instrument could be affected by random light scattering by the particulate matter. The major obstacle in consideration of both of these types of instruments, however, is the prohibitively high cost. In addition, the laser Doppler method has been used only as a laboratory instrument at this time.

SURVEY OF APPLICATIONS

Contacts were made with a number of commercial firms which have had experience in sampling emissions from low velocity sources. This survey revealed that propeller or vane anemometers and rotating vane anemometers find the greatest popularity for low velocity sources. A few investigators also indicated the use of hot wire anemometers.

The popularity of these types of instruments is also reflected in the literature with regard to roof ventilators. Reference A5 cites the use of both hot wire (Anemotherm) and rotating vane anemometers and states that the latter type, either mechanical or electric models, are more convenient for general field use. Reference A6 reports a study in which propeller anemometers with electric output (Gill Model 27100) were successfully used for velocity measurements in roof ventilators.

EPA Method 14 (Ref. A7) specifies the use of vane or propeller anemometers with an electric signal output for velocity measurement in roof ventilator sampling. A single anemometer is to be installed at a point of average velocity, based on a widthwise velocity traverse, for each 85 m of roof ventilator length. Method 14 also specifies that the anemometers be able to withstand dusty and corrosive environments.

Pitot tubes were also used by some investigators for low velocity measurements. The use of a purge gas system with an S-tube was reported to be a useful means of approaching the problem, while an S-tube with a micromanometer reportedly was not successful for very low velocity testing.

In many cases testing with the above-mentioned instruments has been done in conjunction with various types of protective screens, collection hoods, or flow straighteners. In addition, assessments of the accuracy of the instrumentation in these measurement applications are not available, since the actual flow rate and velocity distribution are not known in field applications. In short, the overall situation pointed to the need for further evaluation of the potential use of a number of instruments in low velocity applications.

EVALUATION OF SELECTED INSTRUMENTS

A number of velocity measurement instruments were selected from the basic list given in Table A1 and evaluated as to their suitability for low velocity, unconfined source particulate sampling. Testing of these instruments was accomplished either in a model facility of a roof ventilator (Figs. A1 and A2) or in the field, measuring the flow from roof ventilators atop a secondary aluminum foundry (Figs. A3 and A4). While field test evaluations provide a realistic view of actual conditions to be encountered in using the velocity instrumentation, it is not possible to determine the accuracy of an instrument in the field, as discussed previously. Thus, the roof ventilator model was used to determine the degree of reliability of the various instruments under conditions which simulated those existing in field applications. A summary of the tests of selected instruments follows.

Vane Anemometer - Flowrite Model MRF

This instrument was tested both in the field and with the roof ventilator model. In the field test of the vane anemometer the instrument was fitted with an extension arm and hand held at the exhaust from the foundry roof ventilators. The instrument proved to be sufficiently rugged and easy to use under the awkward field test conditions, and velocity data obtained with the vane anemometer appeared to agree reasonably with expected results.

When tested in the same manner with the roof ventilator model, velocities were determined at 30 points in a plane at the exhaust from the model. The volumetric flow rate determined from these measurements was more than 100% greater than the actual flow rate supplied to the model. This large discrepancy was ascribed to the observed unsteady and circulatory flow emitting from the exhaust; since the vane anemometer cannot detect a reversed flow, the total velocity indicated by the anemometer is expected to be too large. Thus, this type of instrument was deemed unsatisfactory for use in circulatory flow patterns.

Rotating Vane Anemometer - Davis Mechanical Vane Anemometer (Figs. A5 and A6)

This instrument was tested with the roof ventilator model, and volumetric flow rates determined from 24 point velocity surveys were compared with the actual flow rate supplied to the model. The anemometer was fitted with an extension and hand held at the exhaust plane of the model. With this method, at flow rates ranging from about 75m^3/min to 200 m^3/min, the flow rate indicated by velocity measurements with the rotating vane anemometer and the actual flow rate differed by amounts varying from -25% to +75%. This lack of consistency was judged unacceptable.

A second measurement strategy was also evaluated with this instrument. In this method, the anemometer was inserted in the flow through sampling ports located at the base of the

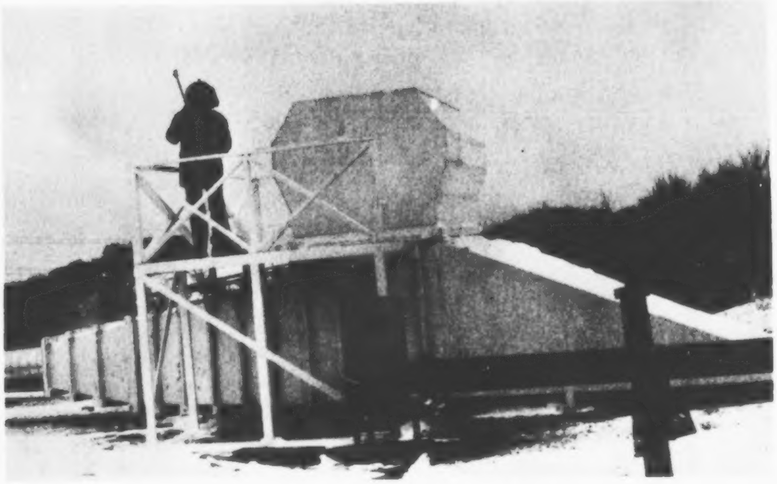


Figure A1. Roof model located at the Medicine Lake Laboratory - looking south

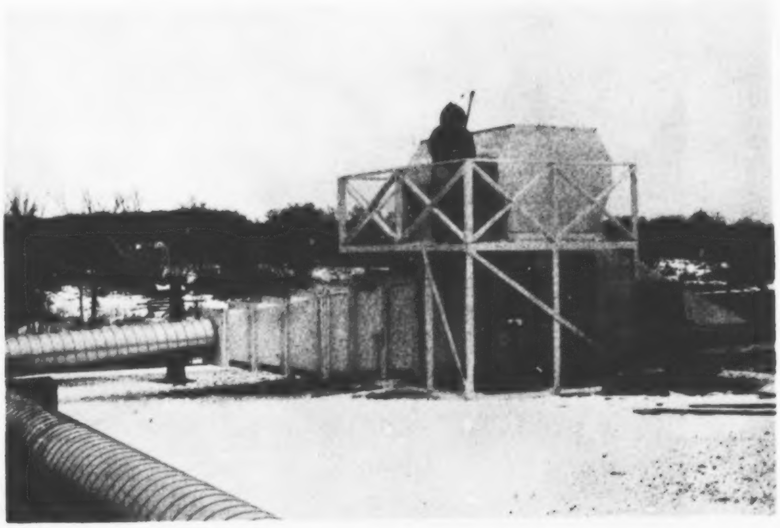


Figure A2. Roof model and ducting located at the Medicine Lake Laboratory - looking southwest

Figure A3. Roof ventilators at Hitchcock Industries, Bloomington, Minnesota, viewed from the northwest

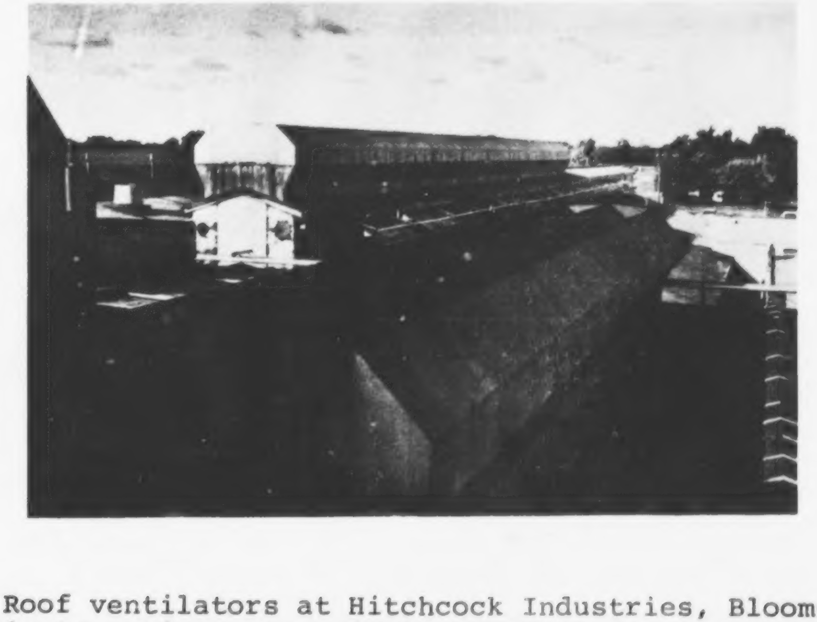


Figure A4. Roof ventilators at Hitchcock Industries, Bloomington, Minnesota, viewed from the east

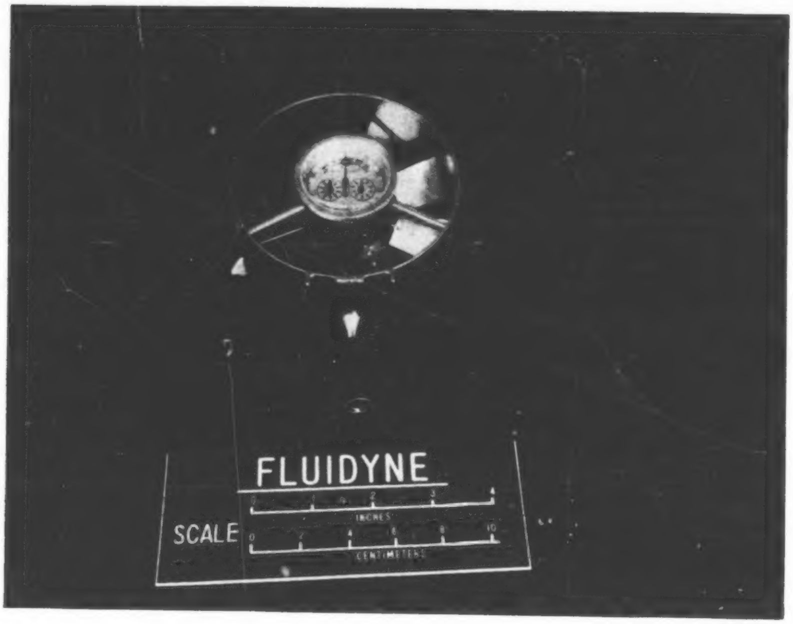

FLUIDYNE
SCALE
INCHES
CENTIMETERS

Figure A5. Davis mechanical rotating vane anemometer with ball swivel attachment

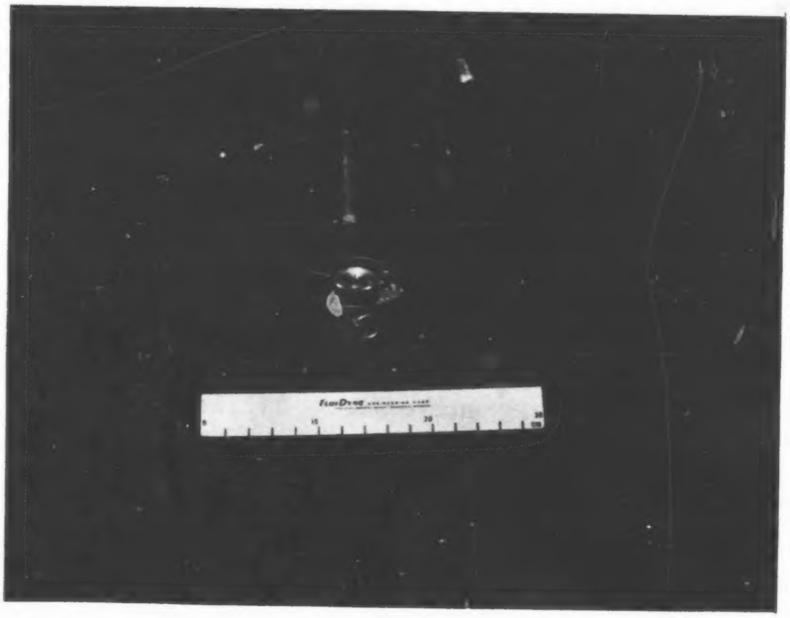


Figure A6. Davis mechanical rotating vane anemometer with extension

ventilator model. This location was deemed more appropriate for particulate sampling since the flow at the base of the model was observed to be more uniform and less dependent on wind conditions. A certain degree of circulatory flow was still present at the base of the model, however, due to the expansion of the inlet to the model downstream of the circular ductwork which supplied the flow (Fig. A2). The flow at the base of the ventilator model could be made more uniform by insertion of a baffle in this diffuser section. Therefore, the flow entering the model at the base could be very uniform, with the baffle inserted, or somewhat circulatory, with the baffle removed. Both types of flow were observed at the field test site, related to the level of activity within the foundry, and the removable baffle thus allowed the simulation of both types of flow entering the roof ventilator model.

Volumetric flow rate determined from 24-point velocity surveys at the base of the model, made with the Davis anemometer, are shown in Fig. A7. As can be seen, the accuracy of the measurements is quite poor, although more consistent than the surveys made at the model exhaust. The results were somewhat better when the baffle was inserted, i.e., when the flow was more uniform, but in both cases the results were unacceptable.

Hot Film Anemometer - Thermo-Systems Model 1610

This instrument was a special version of the standard hot wire anemometer Model 1610 designed to withstand high temperatures (160°C). The instrument was fitted with a special protective collar used successfully in previous studies in which velocities from 0.03 to 4.5 m/sec were measured. However, the instrument still proved to be too fragile for use in the field. When tested at the aluminum foundry, the measurement probe was quickly damaged and the instrument rendered inoperable. Therefore, the hot-wire type anemometer was judged inadequate for the type of field work performed in this study in roof ventilator sampling.

Hot Thermopile Anemometer - Hastings-Raydist Model PCI-30 (Fig. A8)

This instrument was tested extensively with the roof ventilator model, including velocity surveys at the exhaust and at the base of the model. Volumetric flow rates determined from velocity measurements at the exhaust, as well as the base when the flow-uniformity baffle was absent (Fig. A9), differed from the actual by amounts on the order of 60%. This may be attributed to the inability of the instrument to distinguish between velocities 180° apart. This is substantiated by observing the comparison of measured and actual flow rates with the baffle in place (Fig. A9), in which case the agreement was excellent.

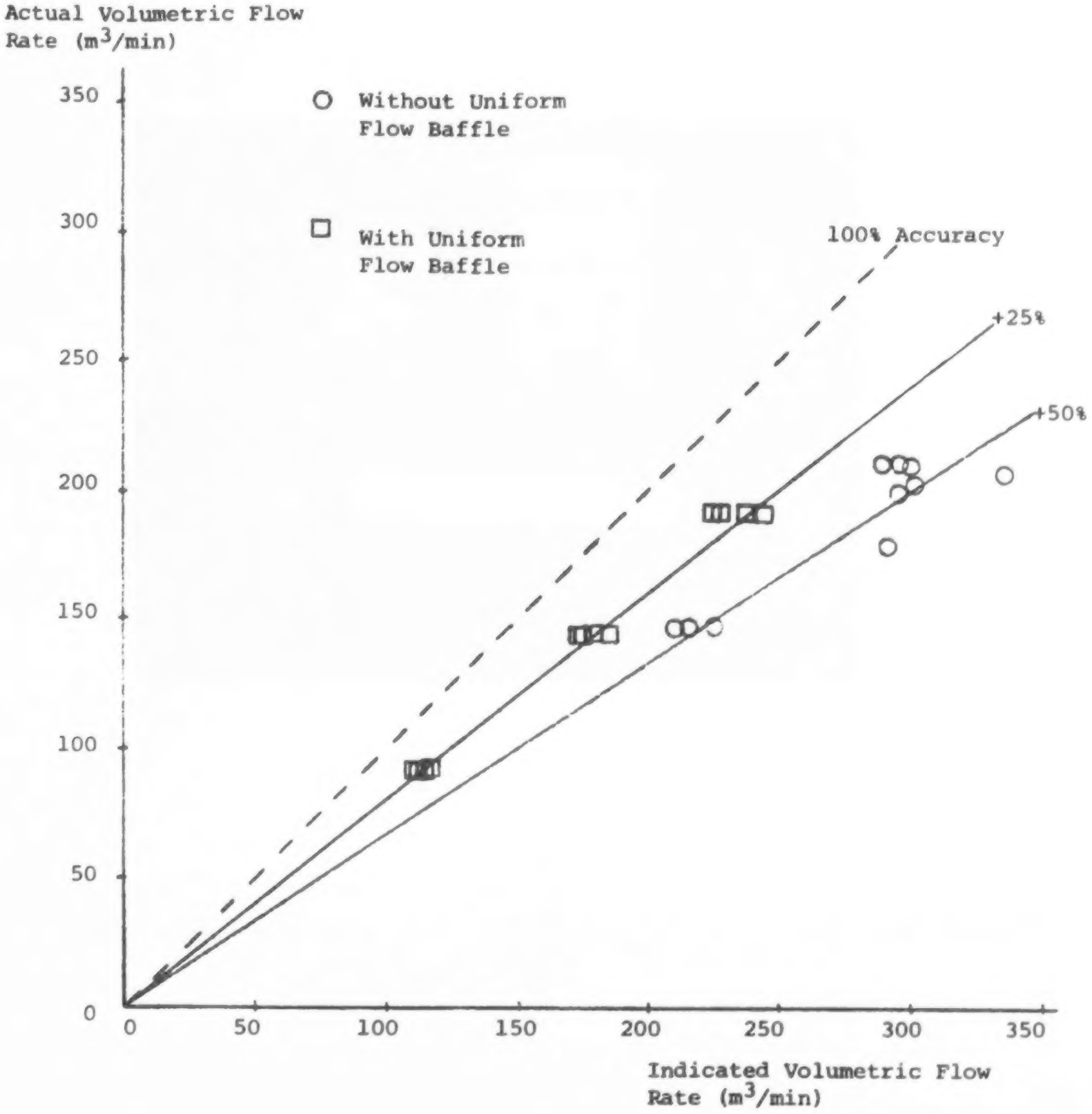


Figure A7. Volumetric flow rate at base of roof ventilator model determined with Davis mechanical rotating vane anemometer

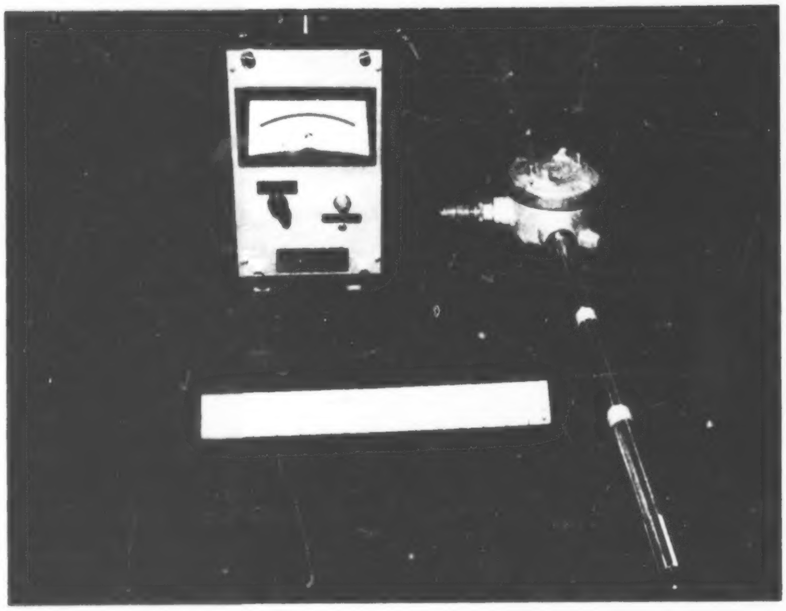


Figure A8. Hastings/Raydist PCI-30 hot thermopile anemometer with meter and extension

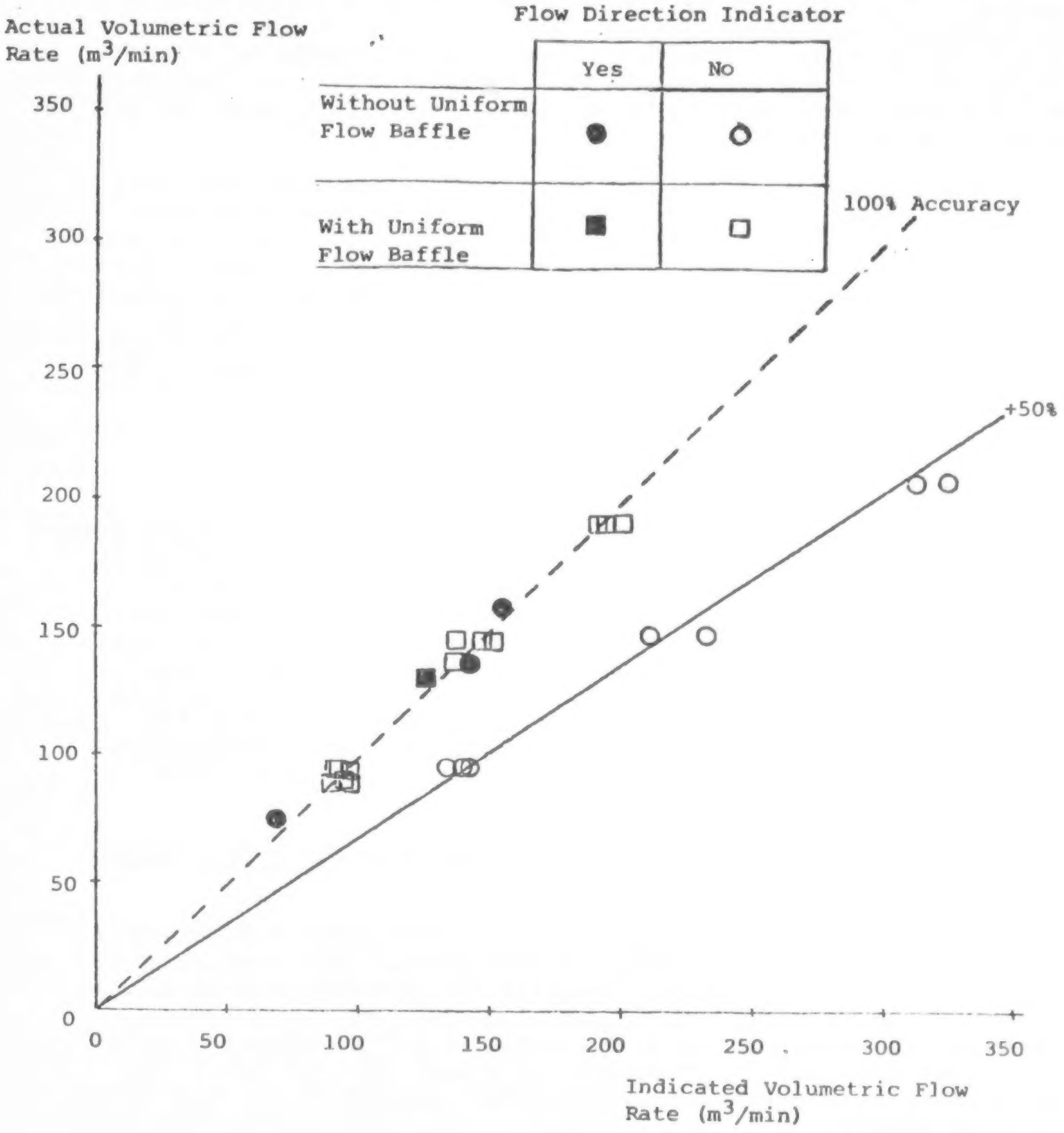


Figure A9. Volumetric flow rate at base of roof ventilator model determined with Hastings-Raydist PCI-30 hot thermopile anemometer

In order to overcome this problem, a lightweight flow direction tuft was attached to the instrument. Several 24-point velocity surveys were then made at the base of the ventilator model, using the flow direction tuft to align the probe with the flow and estimate the flow angle. The volumetric flow rate was then computed from the proper component of the measured velocity as determined from the estimated flow angles. The flow was generally found to be vertically upward or downward, and incorporating the uniform flow baffle eliminated the regions of downward flow. As indicated by Fig. A9, these velocity surveys provided a total volumetric flow rate which agreed very well with the actual flow rate even in the absence of the baffle.

The directional sensitivity of the instrument was also examined (Figs. A10 and A11), and it can be seen that flow direction (to 0° or 180°) can be determined by observing the output of the anemometer if the protective cap is used. Therefore, this instrument could be used to determine flow direction without a tuft, if a means were available to distinguish between flows 180° apart. Pulsating readings make alignment of the probe without a tuft somewhat difficult, however, due to the high sensitivity of the instrument.

Hot Film Anemometer - Thermo-Systems Model 1650 (Fig. A12)

This instrument was found to be somewhat more rugged than the hot wire type anemometer and was lightweight and easy to handle. It was observed that in regions of pulsating or reversed flow, the response time of the instrument was very fast, making reading of the velocity difficult. In two tests of the instrument at the base of the roof ventilator model, with the uniform flow baffle in place, volumetric flow rate determined with the hot film anemometer was less than the actual flow rate by an average of only 3%. This instrument would also need an additional means for determining flow direction in a circulatory flow field.

Wedge Type Hot Film Anemometer - Thermo-Systems Model 1234 H (Figs. A13-A16)

An extensive evaluation of this instrument for potential use in roof ventilator emission measurement was conducted in the roof ventilator model. Details of this evaluation are presented in Ref. A8, which was prepared for the Emission Measurement Branch, Emission Standards and Engineering Division, Office of Air Quality Planning and Standards, of EPA. The particular system which was evaluated consisted of four velocity sensing probes, each with an associated temperature compensating probe. One pair of sensing probes and the various output signal equipment, cables, and switches are shown in Fig. A13.

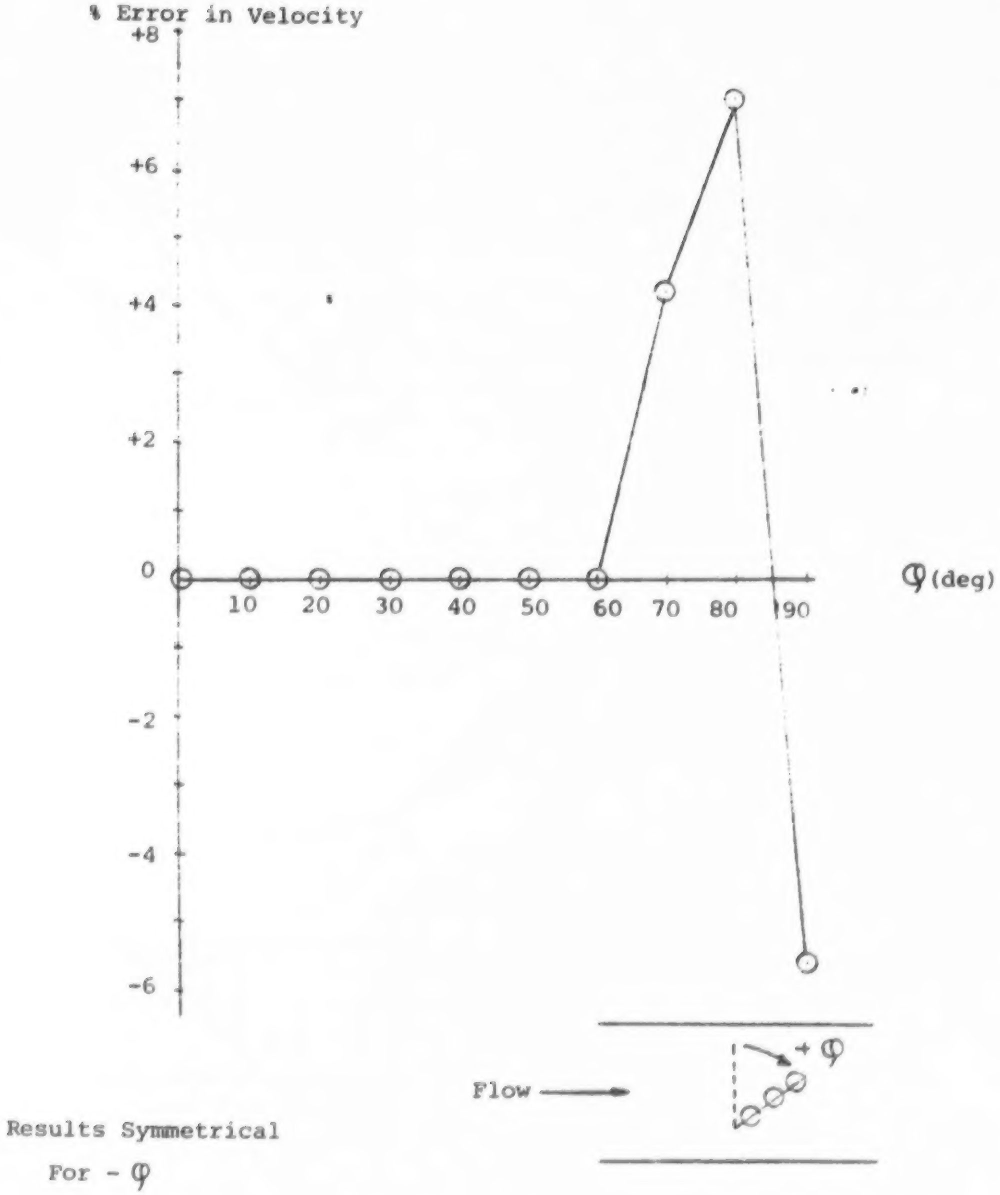
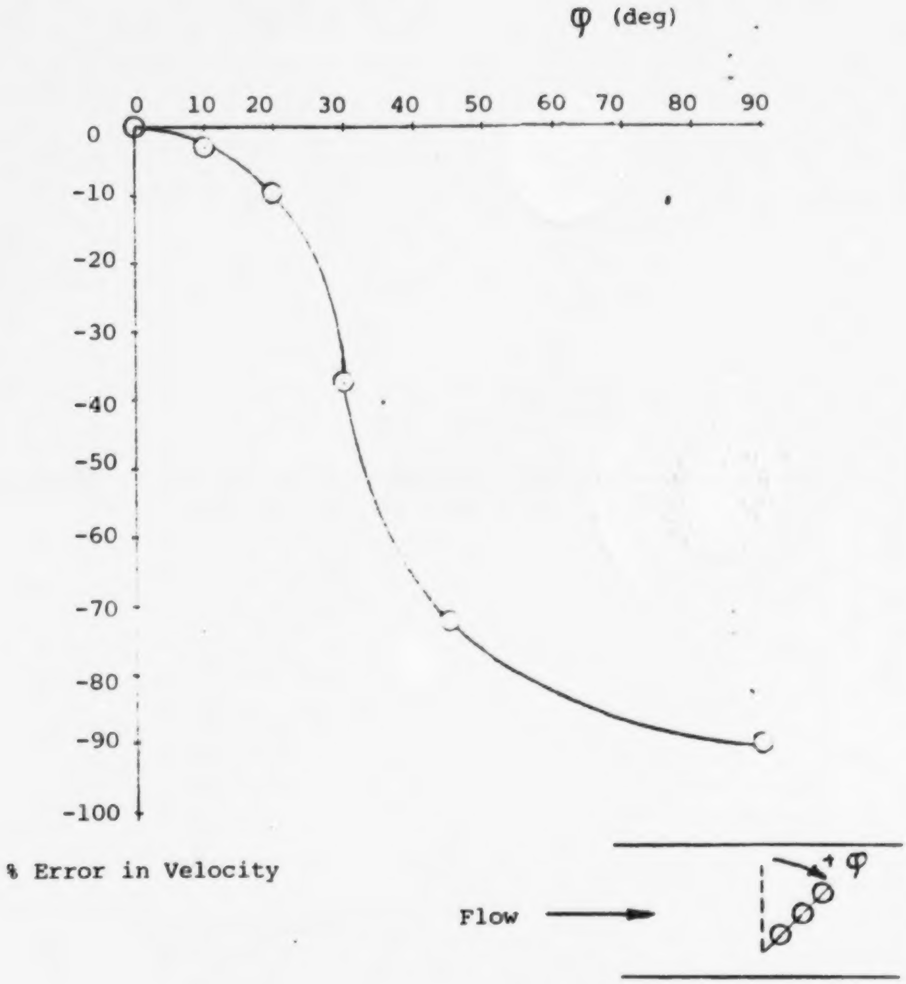


Figure A10. Velocity error with yaw angle for Hastings-Raydist PCI-30 hot thermopile anemometer - without protective cap



RESULTS SYMMETRICAL FOR - φ

Figure A11. Velocity error with yaw angle for Hastings-Raydist PCI-30 hot thermopile anemometer - with protective cap

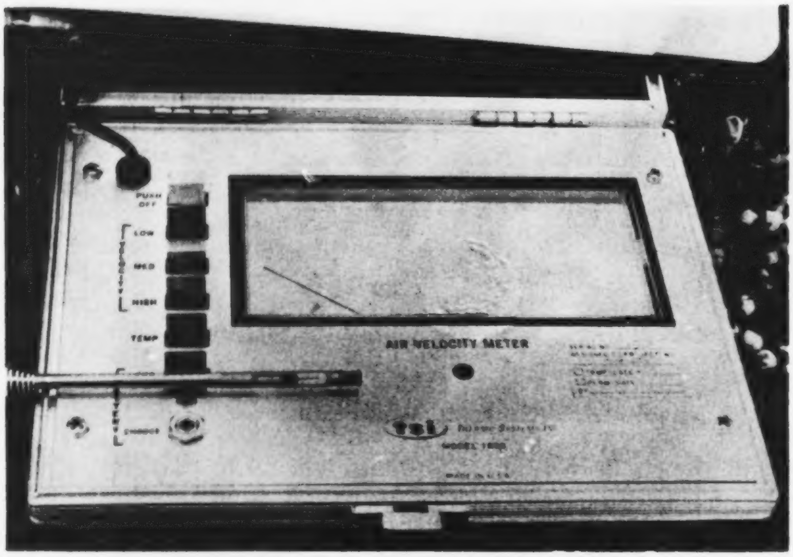

PUSH OFF
LOW
MED
HIGH
TEMP
AIR VELOCITY METER
tsi

Figure A12. Thermo-Systems, Inc. Model 1650 Hot Film Anemometer

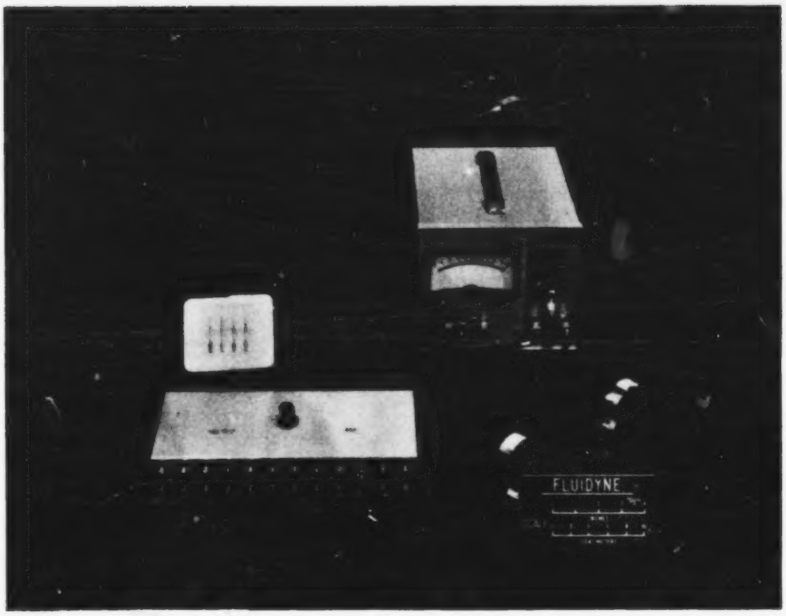


Figure A13. Thermo-Systems, Inc. Model 1234H Hot Film Anemometer System as furnished by manufacturer

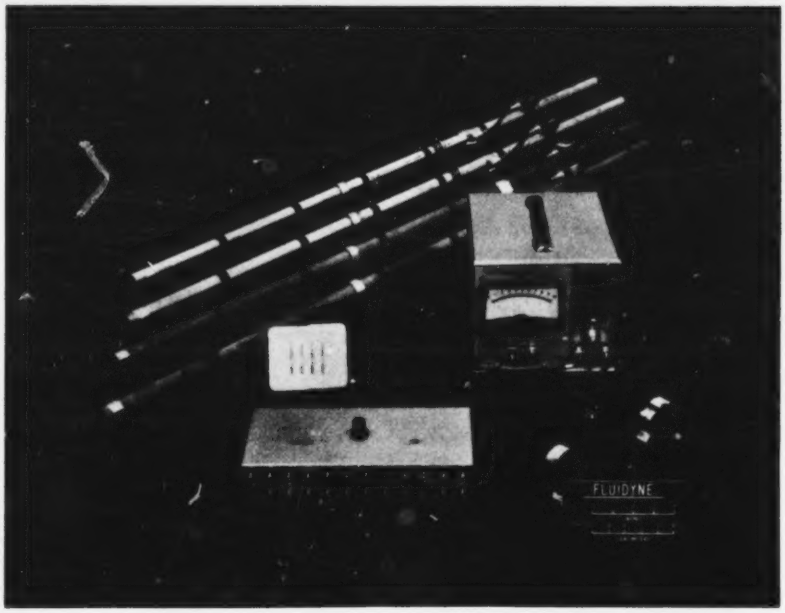


Figure A14. Thermo-Systems, Inc. Model 1234H Hot Film Anemometer System as modified and tested by FluiDyne

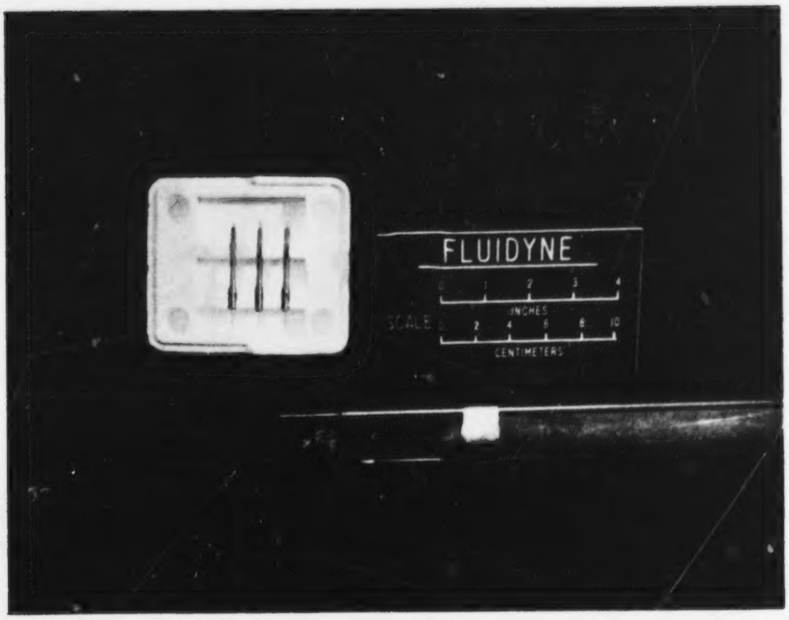

FLUIDYNE
0 1 2 3 4
INCHES
SCALE
0 2 4 6 8 10
CENTIMETERS

Figure A15. Sensor element and temperature compensating element mounted on rigid tubing

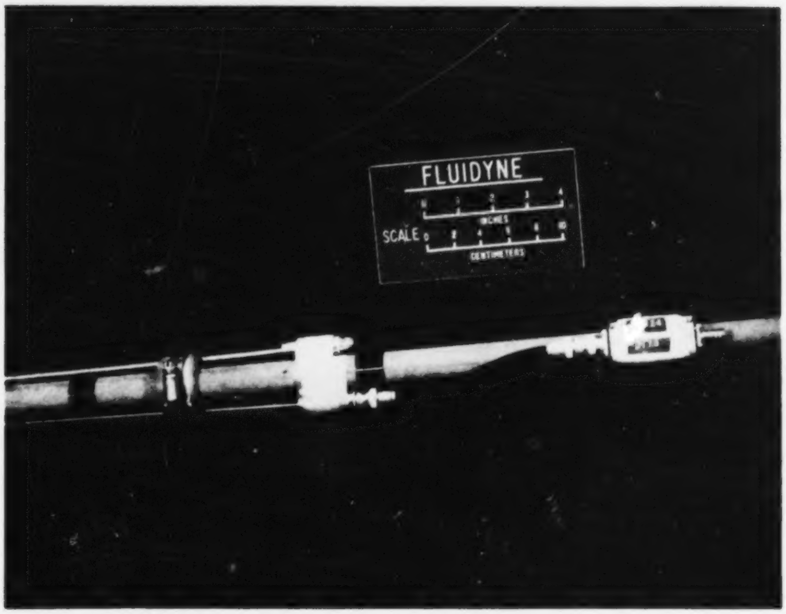

FLUIDYNE
0 1 2 3 4
INCHES
SCALE
0 2 4 6 8 10
CENTIMETERS

Figure A16. Temperature compensating trim resistor box and 15 CM cable insert modification made by FluiDyne

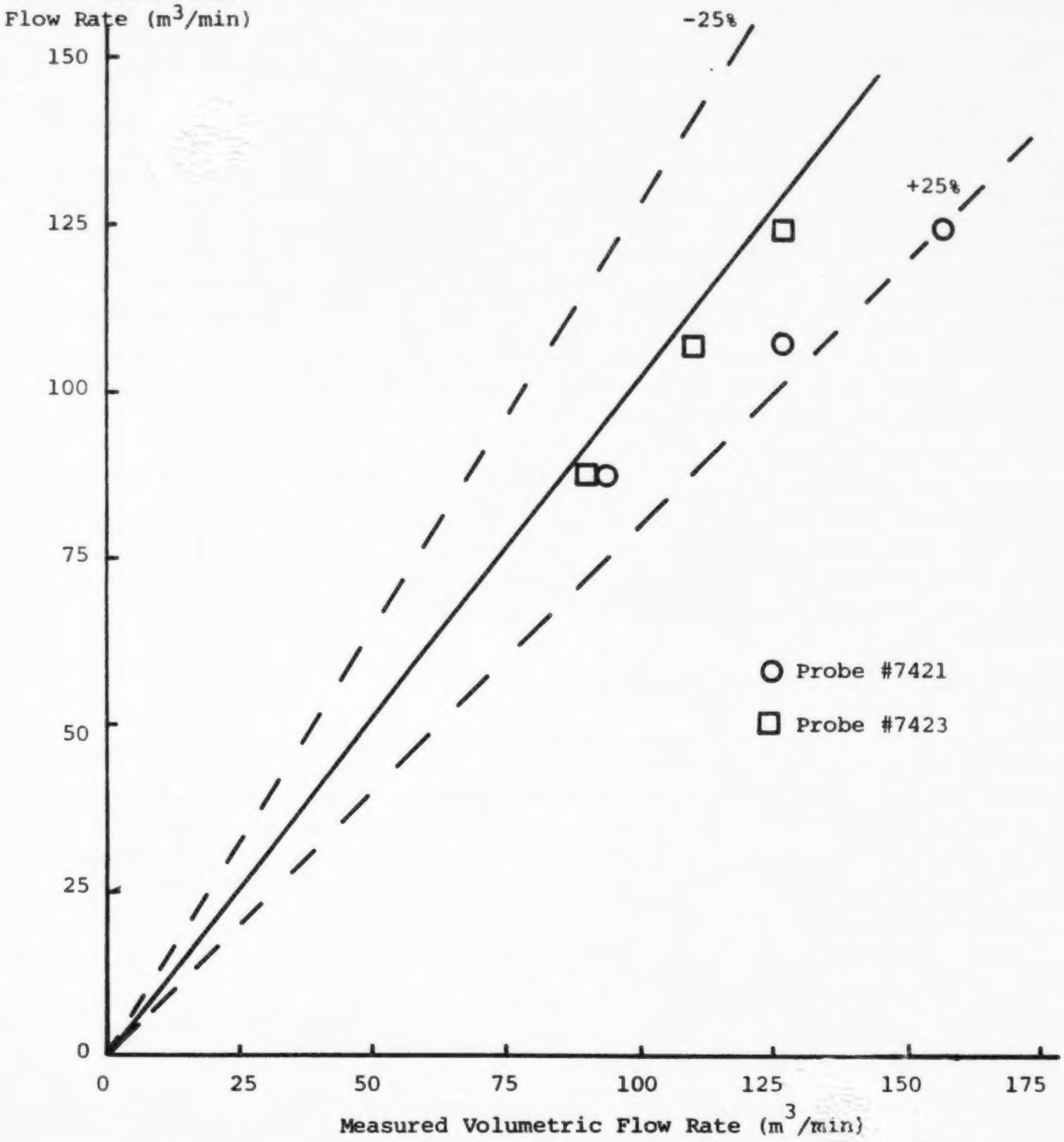


Figure A17. Volumetric flow rate at base of roof ventilator model determined with Thermo-Systems, Inc. Model 1234H hot film anemometer (single probe tests)

Certain modifications were made before the evaluation tests were conducted, as illustrated in Figs. A14, A15, and A16. The velocity sensing and temperature compensating sensors were mounted on lightweight, rigid support tubes to facilitate proper placement and alignment in the roof ventilator model and to prevent sagging and oscillation of the sensing elements in the flow field. Despite these modifications and very careful handling of the equipment, two of the fragile sensing elements were damaged during the course of testing.

Several 24 point velocity surveys were made at the base of the roof ventilator model with the two remaining sensor probes. All measurements were made with the flow straightening baffle in place. The results of these volumetric flow measurements are shown in Fig. A17. This Figure indicates that, when the probes are properly aligned and protected, the accuracy of measurements made with the wedge type hot film anemometer is acceptable. It is not known why the error for the two probes shown in Fig. A17 was different; contributing factors could have been misalignment of the hot film elements in the velocity tests, incorrect reading of the voltage output, or improper calibration by the manufacturer.

A major advantage of this instrument is its temperature rating, which is somewhat higher than other low velocity instruments, as seen in Table A1. The major disadvantage is the very fragile nature of the sensor elements. The instrument also showed a slight degree of yaw sensitivity which might be helpful for aligning the probes in smoother flow streams.

CONCLUSIONS AND RECOMMENDATIONS

The most immediate observation that can be made from the above evaluation of velocity instruments is that accurate measurement of the velocity in the complex flow fields related to such low velocity, partially confined sources as roof ventilators is a very difficult matter. Several factors must be considered in selecting an instrument for such an application, among them:

1) versatility and ease of handling;
2) ruggedness;
3) ability to determine velocity direction as well as magnitude;
4) reasonable accuracy at the very low velocity ranges encountered;
5) ability to operate over ranges of temperature and particulate concentration.

Additional limitations may be placed on the selection of velocity instrumentation by cost considerations.

Considering these overall criteria, and on the basis of the evaluations described above and as considered in these studies, the most likely candidate for general velocity measurement in low velocity, partially confined sources is the hot thermopile anemometer (Hastings-Raydist Model PCI-30). This instrument is relatively light-weight and easy to handle, is very rugged, showed excellent results when used in relatively uniform flow and when used with a flow direction tuft, and operates reasonably well over a fairly broad range of temperature and particulate loading. In addition, the ability to determine flow direction could be utilized in circulatory flow if a means were available to distinguish between flows 180° apart.

The instrument may not be applicable to certain specific applications, however, such as low velocity sources with very high gas temperatures. The overall list of instruments shown in Table Al may be used as a guideline for selection of more appropriate instrumentation in such cases.

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A8. Bezat, Frederick A. and Saari, David P., "Evaluation of Thermo-Systems, Inc. Model 1234H Wedge Type Hot Film Anemometer for Roof Ventilator Velocity Measurements," FluiDyne Engineering Corporation, April, 1977.